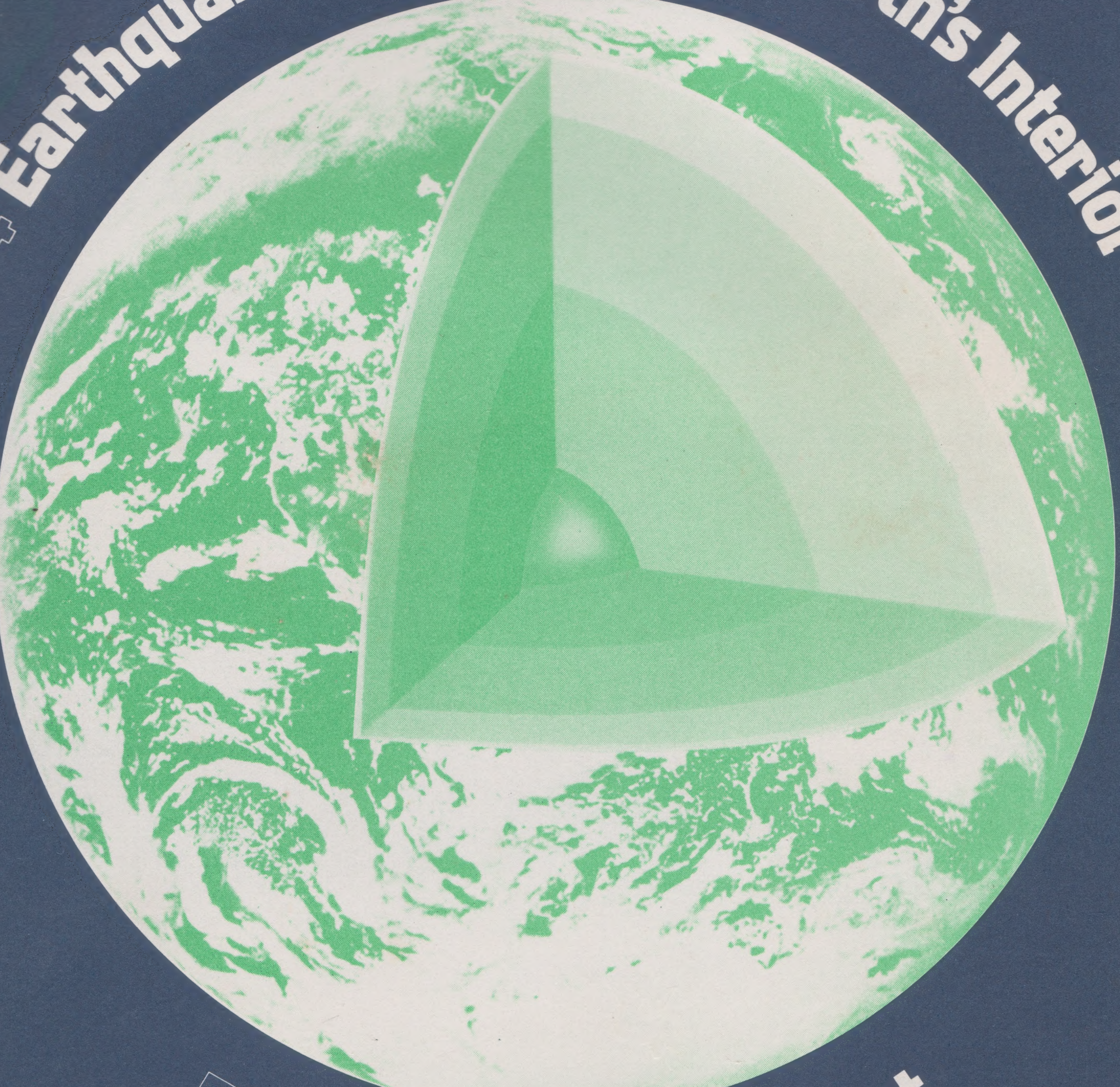
S101 Units 4 and 5

THE OPEN UNIVERSITY

Science : A Foundation Course

4 Earthquake Waves and the Earth's Interior



5 The Earth as a Magnet

The Open University

Science: A Foundation Course

Unit 5
The Earth as a magnet

Prepared by the Science Foundation Course Team

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SCIENCE

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Study guide

The model of the Earth's interior which we have developed in Unit 4 will now be put to a further test: can it make sense of the fact, known for centuries, that the Earth behaves like an enormous magnet?

To understand the *Earth's* magnetism you need first to be clear about what magnetic forces are and about how they relate to electrical currents. The best way of achieving this is by doing experiments. So we have devised a series of simple but instructive Home Experiments, which you should do right at the start of your work on Unit 5. They should not take longer than an hour to do. These experiments deal with the basic properties of magnets. The experiments which demonstrate the relations between magnetic forces and electrical currents would be harder to do at home, so we have devoted part of the television programme (TV 05) to them. You will get more out of this if you have read Sections 5.1 and 5.2 before you see the programme.

The history of the Earth's magnetism is, as you will see in this Unit, recorded in the magnetism of the rocks of the Earth's crust. Studies of this 'palaeomagnetic record' yielded a surprising result—the direction of the Earth's magnetic field has reversed many times over the past 4 000 million years. This provides an important clue to the puzzle of the structure and evolution of the Earth's crust with its continents and oceans, as you will see in Units 6–7. One of the places where you can see direct evidence of magnetic field reversals is in Iceland. A glance at your *World Ocean Floor* map should be enough to tell you that Iceland is an interesting place in other respects too, sitting as it does right on top of the Mid-Atlantic Ridge. The other part of TV 05 was filmed in Iceland, and you will appreciate what you see there better if you have previously read through Sections 3 and 4 of the Main Text.

1 Introduction

In Unit 4 you saw how a model of the Earth's interior could be progressively elaborated to take account of data on the transmission of seismic waves through the Earth. In particular, you learned how the travel times of seismic waves observed at the Earth's surface provided essential clues about the Earth's internal structure and composition. In this Unit we are going to examine another phenomenon originating inside the Earth and yet observable at the surface, namely, the *Earth's magnetism*.

Earth's magnetism

Although it was poorly understood until the twentieth century and is still far from fully understood, the Earth's magnetism has been used by man since ancient times. The ancients first came across magnetism in the form of *lodestone*, a naturally occurring rock which consists of almost pure *magnetite* (a magnetic iron oxide). Lodestone is so strongly magnetic that it can be used to pick up small pieces of iron and, of course, lodestone. It was known to the Greeks by at least 600 B.C.; and by the first century A.D. the Chinese had used it to construct the first compass in the form of a lodestone spoon balanced on a smooth board.

lodestone
magnetite

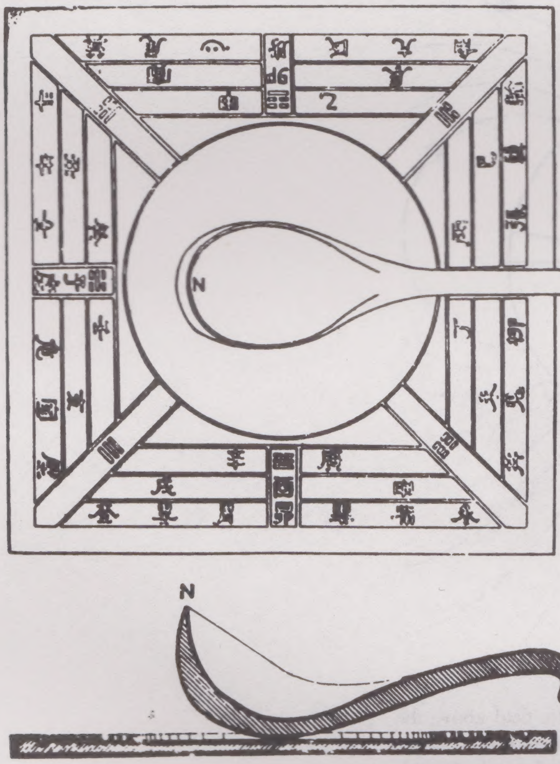


FIGURE 1 Model lodestone spoon and bronze plate reconstructed during the 1940s from an ancient Chinese pattern. This is the earliest form of the magnetic compass. The handle of the spoon points approximately south.

A modern reconstruction of this remarkable instrument is shown in Figure 1. As long as a lodestone spoon of the shape shown is free to rotate, it will always come to rest in an approximately north–south direction because, as we now know, it is influenced by the direction of the Earth's magnetism. Of course, the Chinese did not recognize this influence; indeed, it was not until A.D. 1600, when William Gilbert, a London physician, showed that the behaviour of a compass needle at the Earth's surface was very similar to that of an iron needle placed on the surface of a lodestone sphere, that people began to realize that magnetism is one of the Earth's most fundamental properties. Nevertheless, the Chinese, unlike the Greeks, did observe the *phenomenon* of north–south alignment and put it to use in *geomancy*, the art of prophesy or divining the course of future events. The compass in Figure 1 was thus not used for navigation, although it was not to be long before the Chinese would use the north–south alignment of a magnet in land navigation.

geomancy

What the Chinese had discovered unwittingly was that the Earth's magnetism exerts on a compass needle a set of forces that makes the needle line up in a particular direction. Systematic measurements of this observable effect were not begun until the early nineteenth century, however, and were even then limited to the Earth's surface and the restricted region immediately below it made accessible by mining. Much more recently, of course, aviation and space flight have allowed measurements of the Earth's magnetism to be made far out into space.

If a chart is plotted showing the direction in which a compass needle sets at various points in the space around the Earth, it looks like Figure 2. This diagram has a striking feature which suggests that the origin of the pattern must be inside the Earth rather than external to it (on the Sun or Moon, for example).

What is this feature?

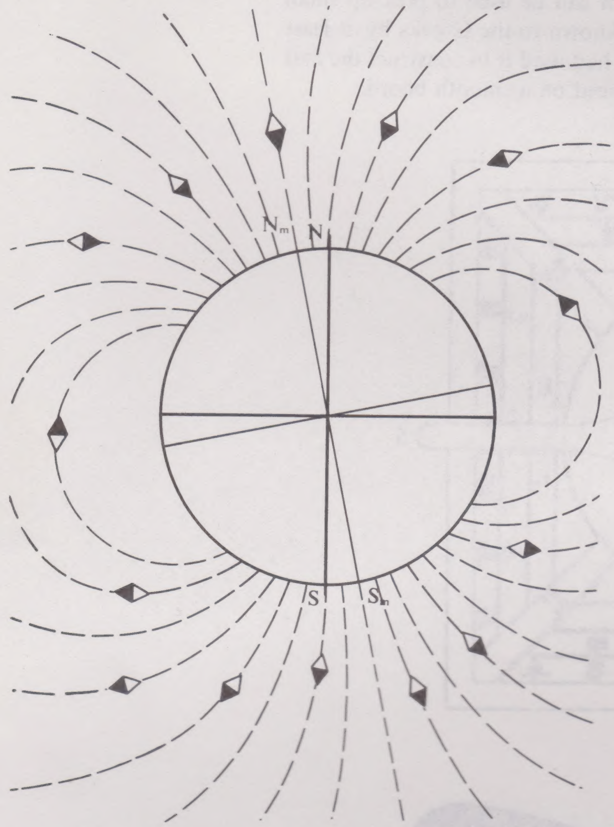


FIGURE 2 The pattern of the Earth's magnetic field above the Earth's surface. N and S are the geographic north and south poles, respectively. The magnetic pattern is symmetrical about the Earth's centre but inclined at 11° to the rotational axis. N_m and S_m are, respectively, the north and south geomagnetic poles, the points at which the axis of the magnetic pattern cuts the Earth's surface. The dark halves of the compass needles are the north poles and point in the direction of the magnetic field (Section 2.2).

The pattern is symmetrical about the Earth's centre. This would be unlikely to happen if it resulted from a magnetic source outside the Earth. You should note, however, that the pattern is not quite symmetrical about the Earth's rotational axis*, the line joining the north and south geographic poles. Instead it is symmetrical about a line sloping at an angle of about 11° to the rotational axis. This is a phenomenon we shall later look at more closely, but it does nothing to invalidate the conclusion that the Earth's magnetism is of internal origin.

Origins apart, it is an observable fact that, at any point in the neighbourhood of the Earth, a test object such as a compass needle comes to rest in a particular

* In the terminology used in Unit 1, this is the Earth's axis of spin. In the case of the Earth, however, it is usual to use the term 'rotational axis'.

direction irrespective of the direction of the needle when it was first put in place. The forces which rotate the test object in this way are produced by a field of force, in this case a *magnetic field*.

magnetic field

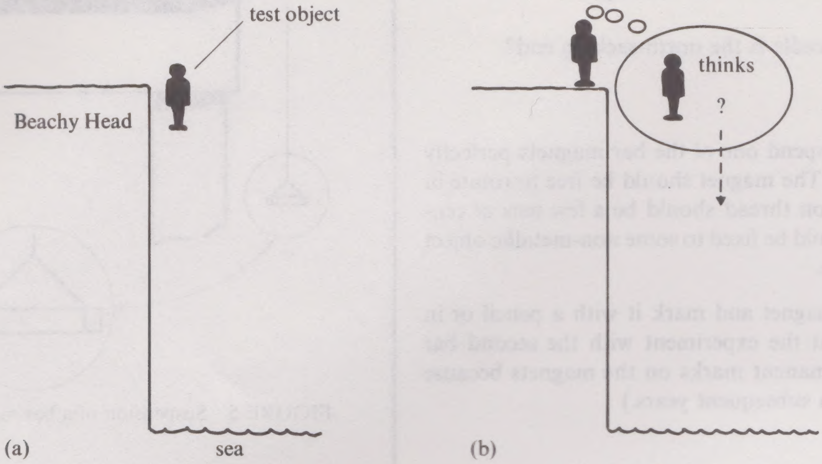


FIGURE 3 The person jumping off Beachy Head in (a) knows from personal experience that the Earth's gravitational field exists a few metres out from the headland. The person only thinking of jumping off in (b) assumes that the gravitational field exists there.

You have come across the idea of a field before, indirectly, in Unit 3. We say there is a gravitational field at some point in the region of the Earth—such as a point a metre or two out to sea from the top of Beachy Head (see Figure 3)—because we know that an object placed there will experience a force in a particular direction. Moreover, we believe that the gravitational field is there even when the object is not. Likewise, we believe that the Earth's magnetic field is there even when the compass needle is not. You should note, however, that whereas the gravitational field causes its test object to *move in* a given direction, the magnetic field causes its test object to *rotate into* a given direction. This difference does not reflect differences in the rules that apply to gravitational and magnetic fields but merely a difference in the natures of the test objects. To understand this point, you must first carry out some simple magnetic experiments. We return to the comparison of magnetic and gravitational fields in Section 2.3.

2 Magnets and compass needles

2.1 What objects experience magnetic forces?

The following terms are explained in the answer to ITQ 1 (page 50):

north-seeking pole
north pole
south-seeking pole
south pole
magnetic pole
attractive force
repulsive force
permanent magnetism
induced magnetism
magnetically soft material
magnetically hard material

You have in your Home Experiment Kit a compass needle, two small bar magnets, a packet of iron filings and some lighter flints. Get these out and try the following experiments.

WARNING Most of these experiments should be performed as far away as possible from iron and steel objects as these are likely to produce magnetic fields of their own which will affect your observations. You should also remove personal items (the keys in your pocket, for example) that may contain magnetic parts.

ITQ 1 What do you observe during Home Experiments 1–13? Make a summary of your discoveries and compare it with ours (on page 50) *after each experiment.*

Home Experiment 1

In accordance with the warning given above, put the magnets well away from the place where you are carrying out this experiment. A good way to store the magnets is to stick them together as shown in Figure 4. With the magnets in this position their fields tend to cancel out, reducing the overall magnetic effect on nearby objects.

Now place the compass on the table and observe the direction in which the needle comes to rest. This direction is approximately north–south. If you find that the needle direction is quite different from the direction you

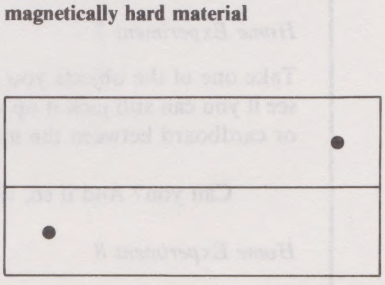


FIGURE 4 How to store a pair of bar magnets. The dots represent the north poles of the magnets.

already know to be north–south (for example, as deduced from the directions of sunrise and sunset, or as shown on your house plans), then you have not taken sufficient heed of the above warning!

Which end of the compass needle is the north-seeking end?

Home Experiment 2

Make a cradle with cotton and suspend one of the bar magnets perfectly horizontally as shown in Figure 5. The magnet should be free to rotate in the horizontal plane. The suspension thread should be a few tens of centimetres long and its upper end should be fixed to some non-metallic object such as the edge of a wooden table.

Determine the north pole of the magnet and mark it with a pencil or in some other temporary way. Repeat the experiment with the second bar magnet. (*Note* Do not make permanent marks on the magnets because these magnets will be used again in subsequent years.)

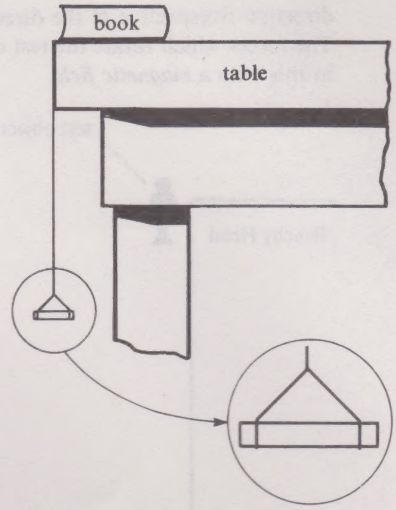


FIGURE 5 Suspension of a bar magnet.

Home Experiment 3

Put one of the bar magnets on a smooth flat surface, such as a polished table top, and move the other magnet across the surface towards the first magnet in various ways, two of which are illustrated in Figure 6.

What effects do the magnets have on each other?

Confirm your results using the compass needle.

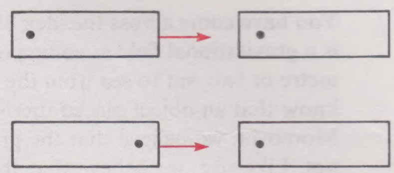


FIGURE 6 Interactions of bar magnets.

Home Experiment 4

Place the two magnets in line, about 10 cm apart, as shown in Figure 7a. Then with an index finger on the top of each magnet, gradually move the magnets towards each other until they touch. Repeat the experiment with the magnets arranged initially as in Figure 7b.

What do you deduce about the forces between the magnets?

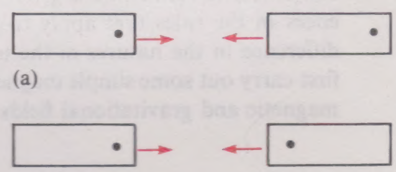


FIGURE 7 Interactions of bar magnets. In (a) the force between the magnets is attractive; in (b) it is repulsive.

Home Experiment 5

Place one magnet in relation to the compass needle as shown in Figure 8 so that the magnet pole nearer the needle is about 5 cm from it.

Can you arrange the second magnet in such a way that the effect of the first is cancelled out—that is, in such a way that the compass needle returns to its original approximately north–south position? If so, what do you deduce from this?

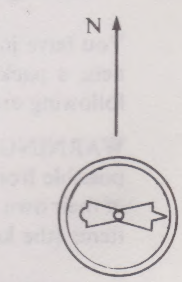


FIGURE 8 The effect of a bar magnet on a compass needle.

Home Experiment 6

Use one of the magnets to try to lift small objects off the table. Experiment with different objects such as matchsticks, drawing pins, ordinary pins, tin tacks, needles, paper clips, screws etc.

What do you conclude from this?

Home Experiment 7

Take one of the objects you succeeded in picking up in Experiment 6 and see if you can still pick it up with the magnet when there is a sheet of paper or cardboard between the magnet and the object.

Can you? And if so, what do you conclude from this?

Home Experiment 8

Take a nail or a screwdriver and stroke it several times from one end to the other in the same direction with one end of one of the magnets.

Will your nail or screwdriver now pick up pins?

Home Experiment 9

Hold one of the magnets in your hand and suspend a nail from it (a nail about 2 cm long is ideal). Then suspend another nail from the base of the first, a third from the base of the second, and so on as far as you can go. You should find that you can suspend at least three or four nails in this way. Now hold the first nail with your free hand and remove the magnet.

What happens?

Home Experiment 10

Repeat Experiment 9 using ordinary pins instead of nails.

What happens now?

Home Experiment 11

Take Figure A (a separate insert in this Unit) and place it face upwards on the table. Place the compass at the intersection of the axes and rotate the paper until the compass needle lies along the line XY and X is to the north. This line will then lie approximately north–south; it is called the *magnetic meridian* through the point at which you are carrying out the experiment.

magnetic meridian

Now remove the compass and replace it with one of the bar magnets. The long axis of the magnet should lie along the XY line with the centre of the magnet above the intersection of the axes, and *the south pole of the magnet should point north.* Place the centre of the compass needle above each of the marked dots in turn and in each case mark the direction in which the north pole of the needle points. One of the directions has already been marked on Figure A as an example. Note that the pivot of the needle is not frictionless; and so the needle may be a little sluggish in its response to magnetic fields. If so, tap the case gently to free the needle.

Do the arrows form a regular pattern?

Home Experiment 12

Place one of the magnets on the table with its north pole pointing approximately south and cover it with a piece of stiff paper or card (about A4 size will do) supported at the edges as shown in Figure 9. Sprinkle iron filings over the paper/card and tap the latter very gently until the iron filings settle in their preferred positions.

What do you observe? How do your observations compare with those from Home Experiment 11?

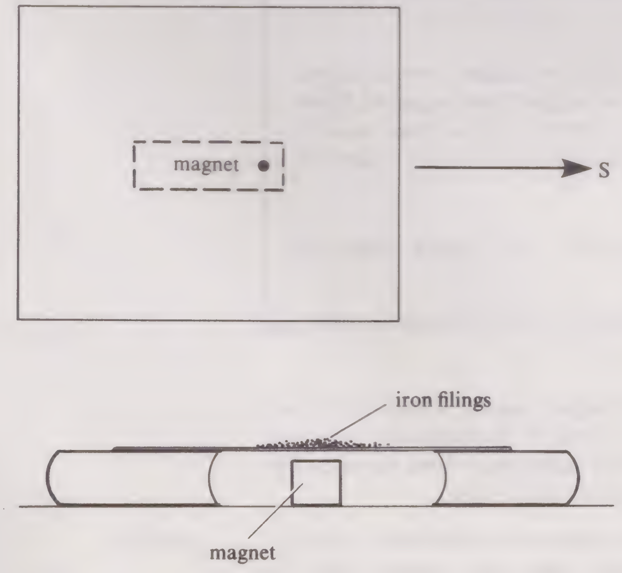


FIGURE 9 How to obtain the magnetic field pattern from a bar magnet, using iron filings.

Home Experiment 13

Remove the magnet and repeat Home Experiment 12 without it.

What do you observe?

2.2 The shapes and magnitudes of magnetic fields

From your observations with the compass needle and iron filings, you should already have an idea of the shape of the magnetic field produced by a bar magnet.

But was the field pattern revealed in Home Experiments 11 and 12 due to the magnet alone?

Strictly, no. Remember that the compass needle points in a particular direction even when there are no magnets around, because the Earth's magnetic field is still there. The field pattern revealed by Home Experiments 11 and 12 was really a combination of those from the magnet and the Earth. However, we concentrated on a region so close to the magnet that the field there from the magnet was much stronger than that from the Earth.

Further away from the magnet, on the other hand, the field from the magnet itself becomes smaller; so there is a region where the field from the magnet and that from the Earth are of about the same strength. And at greater distances from the magnet the chief effect will be that of the Earth's field.

Bearing in mind the result of Home Experiment 5, what would you expect to happen to the combined field of the Earth and a magnet in regions where the strengths of the two individual fields are about the same?

From Home Experiment 5 we concluded that magnetic fields add up as long as the directions of the fields are taken into account. Thus two fields of equal strength but opposite direction would, when combined, produce no net field at all; they would cancel. But if the two fields were in the same direction they would, when combined, produce a field with a strength twice that of each individual field; they would reinforce. So in a region where the Earth's field and a field from a magnet are about equal in strength, we might expect to find points where the field has a strength of anything up to twice that of the Earth's field alone.

Unfortunately, you cannot determine the strength of a magnetic field with the equipment in your Home Experiment Kit; so you cannot detect the effects of reinforcement. But you can find points at which there is no net field at all.

Home Experiment 14

Set up Figure A again with the line XY lying in the magnetic meridian (see Experiment 11) and with the north pole of the magnet pointing south. Place the compass needle close to the north pole of the magnet and then move it slowly along the line XY towards Y. Repeat the experiment between the south pole of the magnet and X.

What do you observe and what do you deduce from the observations?

On the line XY close to the magnet, the compass needle points south and continues to do so as the needle is moved towards Y. As the needle is moved further, however, it reaches a point at which it points east–west. Even further away from the magnet the needle swings round to point north.

The point at which the needle points east–west is known as a *null point*; there the Earth's field and the field from the magnet are equal and opposite and thus cancel. There is another null point between the south pole of the magnet and X.

null point

Between the null points and the corresponding magnetic poles the field from the magnet is stronger than that from the Earth, whereas on the other side of the null points, away from the magnet, the Earth's field predominates.

If you were to plot the complete field in Experiment 11 you would obtain the pattern in Figure 10a. This represents the combined field from the bar magnet and the Earth*. If you were to remove the magnet and replot the field in the same area you would obtain the pattern shown in Figure 10b. This represents the Earth's field alone. If you had a device, known as a *magnetometer*, which measured the strength as well as the direction of a magnetic field, you would be able to measure the strengths of the fields in Figures 10a and 10b, and, by subtracting one set of measurements from the other, you would be able to determine the field from the bar magnet alone. This field is shown in Figure 10c.

magnetometer

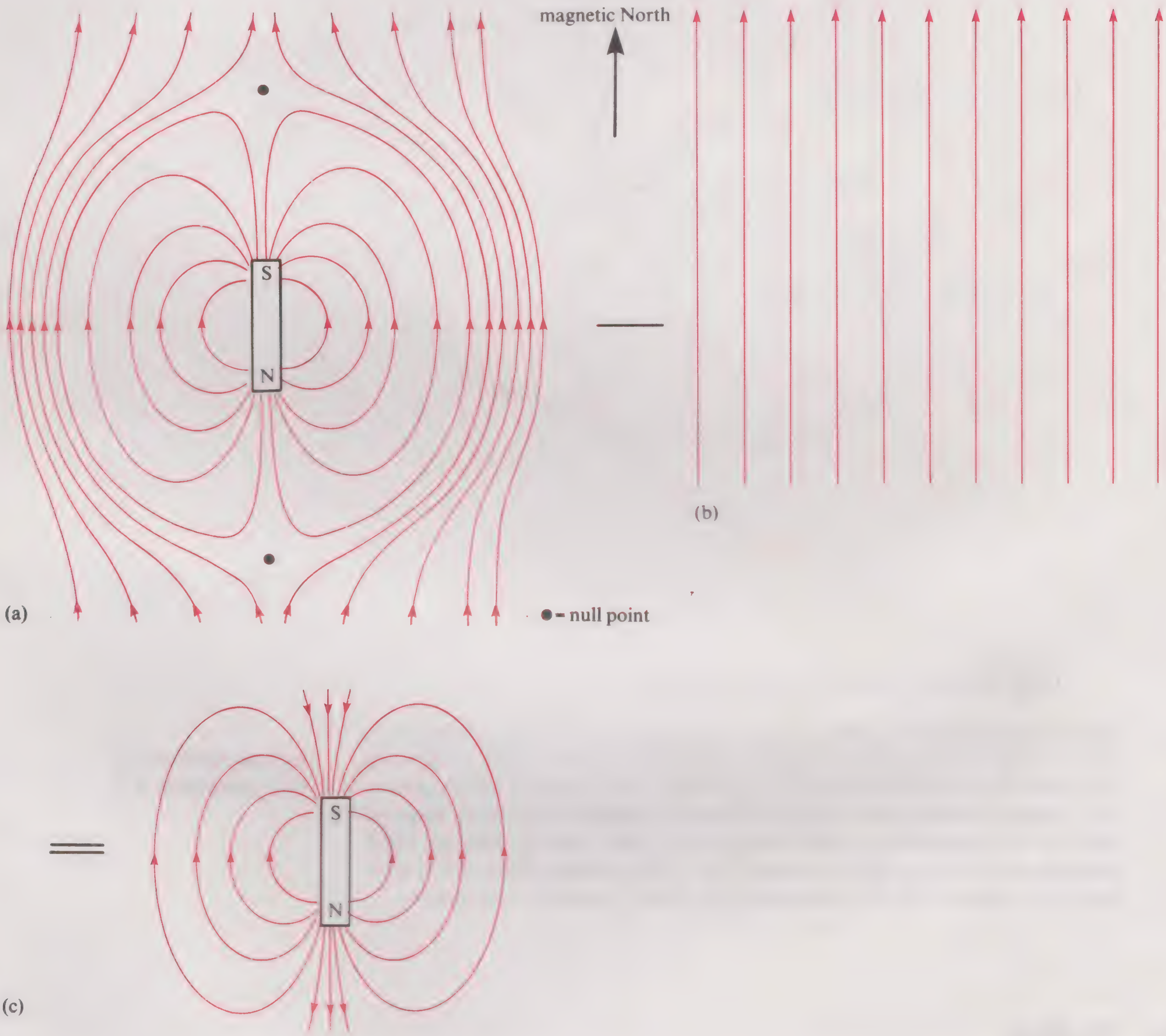


FIGURE 10 (a) The combined field pattern from a bar magnet and the Earth with the north pole of the magnet pointing south; (b) the Earth's magnetic field alone. When the field in (b) is subtracted from that in (a), the field in (c) remains. This is the field due to the bar magnet alone.

What do you deduce from comparing Figure 10c with Figure 2?

You should be able to see that the patterns are identical. A field of this shape is known as a *dipole field* because it is produced by a simple magnet with two poles, north and south. Incidentally, you should bear in mind always that Figures 2

dipole
dipole field

* The lines used to represent the pattern of a field of force are *not* lines of equal field strength.

and 10 are only two-dimensional representations of fields that really exist in three dimensions. The three-dimensional nature of a bar magnet field is better illustrated in Figure 11.

There is one other thing you should have noticed in the comparison of Figures 2 and 10c. As Figure 10c shows, the direction of the magnetic field around a bar magnet is outwards from the north pole and inwards at the south pole; in other words, the north pole of a compass needle points away from the magnet's north pole and towards its south pole.

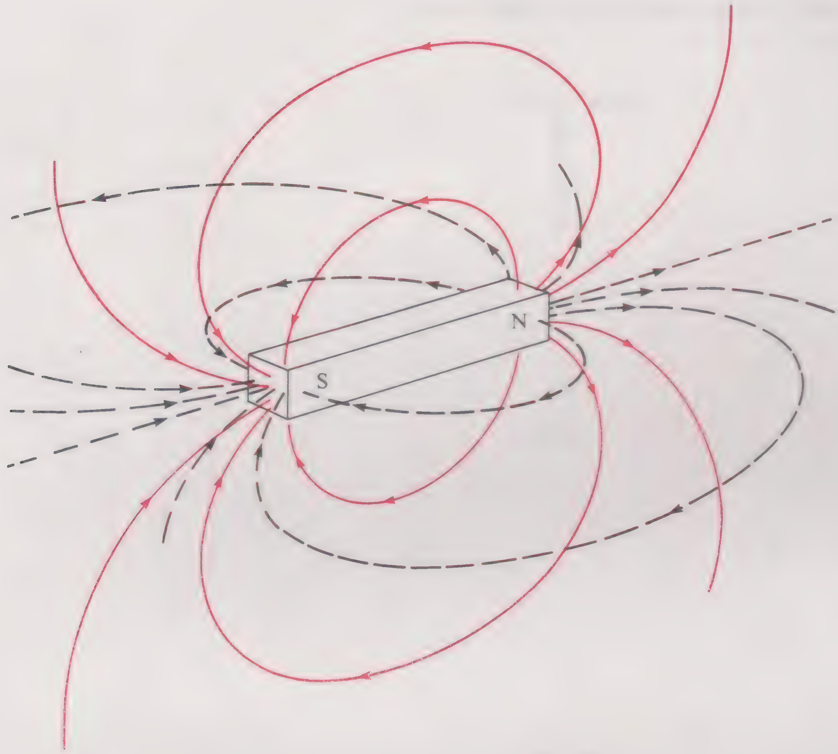


FIGURE 11 Three-dimensional impression of the dipole field.

Look at Figure 2 again. What do you notice?

You should see that the north poles of the compass needles are pointing *away* from the region of the *south geomagnetic pole* and *towards* the region of the *north geomagnetic pole*. This is because, by convention, the north and south geomagnetic poles are named not to correspond with the polarity of the Earth's magnetic field but to correspond with the hemispheres in which they lie. Thus the north geomagnetic pole is so called because it lies in the northern hemisphere; it actually corresponds with the south pole of the Earth's magnetic field source.

south geomagnetic pole
north geomagnetic pole

2.3 The dipole

In Section 2.2 we said that the direction of a magnetic field at a particular spot is the direction in which the north pole of a compass needle at that spot would point. The direction of a magnetic field at a particular spot is also the direction in which an isolated magnetic north pole would move if placed at that spot.

Why, then, is it usual to plot magnetic field directions using a compass needle rather than a magnetic north pole?

You may have guessed the answer to this by now. Isolated poles, whether north or south, do not exist—or if they do, no one has yet succeeded in observing one. It is impossible to have a north pole without a closely associated south pole, and vice versa. The minimum number of magnetic poles that can exist naturally is two; or in other words the dipole is the simplest magnetic source that can occur.

This has two important consequences:

1 You will recall that at the end of Section 1 we left hanging the question of why it is that an object in a gravitational field moves in a given direction whereas a test object in a magnetic field rotates into a given direction. The non-existence of single magnetic poles explains why. Figure 12 shows a dipole in a magnetic field. The north pole experiences a force to the right, in the direction of the field, and would move in that direction if it were free. But it is not free, for it cannot escape the associated south pole which experiences an equal force to the left, against the field direction. In other words, the forces on the dipole are equal and opposite; so there is no net force in any direction, and the dipole cannot move laterally. What does happen, though, is that the dipole rotates until it lies along the field with the north pole pointing in the field direction.

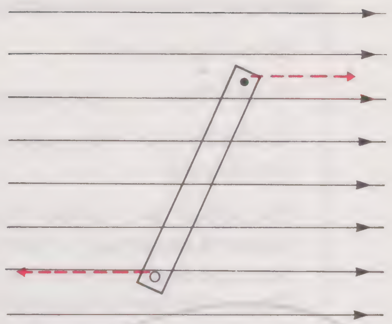


FIGURE 12 A dipole in a uniform magnetic field (directed to the right). The north pole experiences a force in the field direction; the south pole experiences a force in the opposite direction. The net result is no lateral motion but rotation of the dipole into the direction of the field (i.e. with the north pole pointing in the field direction).

Can you imagine any circumstances in which a magnetic dipole would move laterally as well as rotate?

In the example shown in Figure 12, we assumed that the magnetic field strengths at the positions of the north and south poles were equal—in other words, that the magnetic field was uniform over the region covered by the dipole. But if the field were one that varied over very short distances (i.e., a non-uniform field) the field strengths at the north and south poles would not be the same and hence the forces experienced by the poles would not be equal. If, for example, the field at, and hence the force on, the north pole were the greater, the dipole would not only rotate into the field direction but would also move laterally to the right.

Have you actually observed such an effect?

Yes, you have. Magnets and magnetized objects were made to move laterally in some of your experiments (e.g. Home Experiments 3 and 6). Lateral movement occurred because close to a bar magnet the field is very non-uniform.

2 As you saw in Unit 3, the gravitational force, and hence the field (which we will call H_g), at a point is inversely proportional to the square of the distance (r) between the point and the centre of the mass producing the field, that is, $H_g \propto r^{-2}$. This is called the inverse square law and, in principle, it applies equally to magnetic fields. The magnetic field (H_m) at a point is inversely proportional to the square of the distance (r) between the point and the centre of the pole producing the field, that is, $H_m \propto r^{-2}$. But as we have seen, the pole producing the field cannot exist in isolation; it must be associated with an opposite pole which produces another field in a different direction. The net field at the point in question is thus reduced. In fact, the field (H_d) at a distance (r) from the centre of a dipole is given by $H_d \propto r^{-3}$. Thus doubling the distance from a magnet reduces the field by a factor of 8, trebling the distance reduces the field by a factor of 27, quadrupling the distance reduces the field by a factor of 64, etc.

Finally, there is one other very striking difference between magnetic and gravitational fields.

Can you think what it is?

If you bring one of your magnets down slowly towards an ordinary pin, the pin will jump up to the magnet. On the other hand, if you were to replace the magnet with a piece of lead of the same size, there is no way in which you could get the pin to jump. Indeed, the pin would not jump even if the piece of lead were many, many times bigger. The gravitational force between the lead and the pin is very much smaller than the magnetic force between the magnet and the pin. Or to put it another way, for sources of a comparable size, magnetic forces are very much larger than gravitational forces.

2.4 Magnetism and heat

In view of the similarity between the field pattern of the Earth and that of a dipole, you are probably speculating already about whether there is a large bar magnet, or something similar, in the Earth. We shall return to this question later in the Unit, but in the meantime here is something to be thinking about:

Home Experiment 15

WARNING 1 Take care not to burn yourself during this experiment.

WARNING 2 You must under no circumstances heat either of the two bar magnets.

The lighter flints in your Home Experiment Kit are made from a weakly magnetic man-made substance. Check that they are weakly magnetic by picking a couple of them up with one of the magnets. Now place these two flints on the sheet of aluminium from your Kit and heat them slowly putting the aluminium sheet on a ring of a gas or electric cooker. After about 30 seconds (with gas) or several minutes (with electricity) try to pick up the flints (carefully) with the magnet.

What do you find?

You should find that the flints can no longer be picked up; they are no longer magnetic and no longer capable of sustaining even induced magnetism. Heat destroys magnetism. Each magnetic substance has a temperature, known as its *Curie point*, above which the substance is no longer capable of sustaining magnetism. For the lighter flints the Curie point is about 125 °C, but all Curie points lie below 1 200 °C and those of most common magnetic materials lie below 800 °C.

Curie point

From this fact you should be able to draw an important conclusion about whether or not the Earth's magnetic field may be produced by a bar magnet in the Earth's interior. While you are thinking about that, we shall go on to look at the main features of the Earth's magnetic field in more detail. We shall also examine how the field has changed through historical and geological time. Finally we shall speculate on how the Earth's field is generated.

In studying the history of the Earth's magnetic field you are in for a few surprises, as indeed were the scientists who, during the 1960s, discovered that the Earth's dipole has reversed its poles (north to south, south to north) many times throughout geological time. As you will see when you study Units 6 and 7, this remarkable discovery has provided crucial evidence about the structure and evolution of the Earth's crust.

2.5 Objectives of Section 2

Now that you have completed Section 2, you should be able to:

(a) Use the following terms correctly and/or recognize whether or not they are being used correctly:

(introduced in Section 2.1) north-seeking pole, north pole, south-seeking pole, south pole, magnetic pole, attractive force, repulsive force, permanent magnetism, induced magnetism, magnetically soft material, magnetically hard material, magnetic meridian; (introduced in Section 2.2) null point, magnetometer, dipole, dipole field, north geomagnetic pole, south geomagnetic pole; (introduced in Section 2.4) Curie point.

(b) Describe (in words or pictures, as appropriate) the main properties of a bar magnet and its magnetic field and make simple deductions from them.

SAQ 1 (*Objectives (a) and (b)*)

Fill in the word(s) missing from each of the following statements:

(a) The only common natural metal capable of becoming strongly magnetic is (i) .... .

(b) The north pole of one bar magnet attracts the (i) .... pole of another, whereas the south pole of one bar magnet attracts the (ii) .... pole of another.

(c) If at a given spot there are two magnetic fields, one of which is equal in strength and opposite in direction to the other, the net field at that spot is (i) .... .

(d) At any location, the direction in which a compass needle points is known as the local (i) . . . .

(e) The (i) . . . . pole of a bar magnet will repel the south pole of a compass needle.

(f) A piece of iron or steel that sustains magnetism even when the magnetizing source is removed is said to possess (i) . . . . magnetism.

(g) In a compass needle the pointed end is usually the (i) . . . . pole, or (ii) . . . . pole.

(h) The south geomagnetic pole corresponds to the (i) . . . . pole of the Earth's magnetic source and lies in the (ii) . . . . hemisphere.

(i) A (i) . . . . may be used to measure both the direction and strength of a magnetic field.

(j) Magnetically (i) . . . . material is relatively difficult to make into a permanent magnet, but once the permanent magnetism is acquired it is not easily lost.

(*SAQ answers begin on p.* 52.)

SAQ 2 (*Objective* (*b*))

A bar magnet is placed in a room that has been completely shielded from the Earth's magnetic field. Sketch, from memory, the pattern of the magnetic field you would expect around the magnet and indicate by arrows the direction of the field.

SAQ 3 (*Objectives* (*a*) *and* (*b*))

Decide between the alternative terms provided for each of the following statements:

(a) The repulsive force between the south poles of two bar magnets *increases/decreases* as the poles approach each other.

(b) The magnetic field near the centre of a bar magnet is *weaker/stronger* than those near the poles.

(c) A piece of iron picked up by and then removed well away from a magnet possesses induced magnetism when attached to the magnet but may or may not possess *induced/permanent* magnetism when it is removed.

(d) The Earth's magnetic field resembles in shape that produced by a *dipole/single pole.*

(e) At a null point the fields due to a magnet and the Earth are *equal/unequal* in strength and opposite in direction.

(f) A dipole placed in a uniform magnetic field does not *move laterally/rotate.*

(g) If an isolated south pole could exist it would, when placed in a magnetic field, move *in/against* the field direction.

(h) If at a given spot there are two magnetic fields, one of which has a strength of x units and one of $3x$ units, the resultant field at the spot is $2x/4x$ if the fields act in the same direction.

(i) Any magnetic material will lose its magnetism at its *Curie point/null point.*

SAQ 4 (*Objective* (*b*))

Figure 10a shows the combined magnetic field from the Earth and a bar magnet when the north pole of the bar magnet points south. The fields from the Earth and magnet alone are shown, respectively, in Figures 10b and 10c. Sketch the field you would expect from a bar magnet placed in the Earth's field with the *north* pole of the magnet pointing *north.* Indicate the directions of the magnetic field and indicate roughly where you would expect to find the two null points.

3 The Earth's magnetic field

3.1 The magnetic elements

The Earth's magnetic field (often called the geomagnetic field) is similar to that of a bar magnet at the Earth's centre, and the field of a bar magnet is dipolar. Moreover, the dipole is the simplest magnetic source that can exist. The simplest possible magnetic field the Earth could have is therefore that of a dipole whose axis (that is, the line passing through the north and south poles of the dipole) coincides with the Earth's rotational axis. Now as you have already seen in Section 1, the Earth's dipole slopes at an angle of 11° to the rotational axis. *For the moment, however, let us first consider the characteristics of the field produced by a dipole lying at the Earth's centre* (geocentric) *and aligned along the Earth's rotational axis* (axial). The configuration of such a field with respect to the Earth is shown in Figure 13.

geocentric
axial

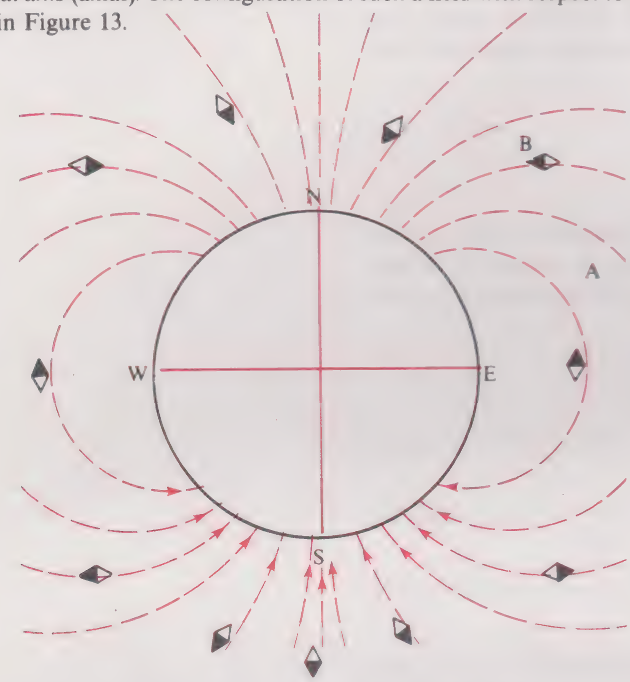


FIGURE 13 The geocentric axial dipole field.

Where are the north and south geomagnetic poles?

Since the dipole axis and the rotational axis coincide, the north and south geomagnetic poles coincide, respectively, with the north and south geographic poles.

Now look at Figure 13 again very carefully. Imagine that you are standing at the equator with a compass needle of the sort you have in your Home Experiment Kit.

Which way will the needle point?

It will point due north because the magnetic field points north—that is, towards the north geomagnetic pole which coincides with the geographic pole.

Now imagine yourself walking along a line of longitude from the Equator towards the north geographic pole.

Which way will the needle point as you travel?

It will always point due north for the same reason that it pointed due north at the Equator.

The fact that the compass needle points north will probably not surprise you, if only because your general knowledge probably told you that compass needles

point north. But knowing what you now know, you should be a little puzzled, if not actually surprised. Look at the compass needles marked A and B in Figure 13. Are they pointing north? No, they are not. They are pointing along their respective field directions, that is, along lines that enter the south pole of a small imaginary bar magnet at the Earth's centre.

How do you explain the apparent discrepancy between Figure 13 and the known behaviour of a compass needle?

The explanation is that a compass needle such as the one in your Home Experiment Kit is mounted on a vertical pivot or axis and is constrained to move only in the horizontal plane. When held horizontally, it can rotate, but it cannot dip; it can move only in two dimensions. So it comes to rest not along the direction of the magnetic field but along the part of the magnetic field that acts in a horizontal direction. This is known as the horizontal component of the magnetic field. By contrast, the compass needles represented in Figure 13 are not constrained; they point in the total field direction. When thinking about this, remember that the picture represented by Figure 13 is really three-dimensional. You must imagine a three-dimensional system rather like that in Figure 11, with compass needles free to set in any direction.

Indeed, do just that. Imagine again that you are standing on the Equator not with a constrained compass needle but with a needle free to set in any direction. (This is an imaginary instrument, of course; it would be difficult to construct one.)

How will the needle set?

It will lie in the horizontal plane and point due north because, as you should be able to see from Figure 13, that is the field direction at the Equator.

But what will happen to the needle as you travel along a line of longitude towards the north pole?

It will continue to point generally northwards, but at the same time it will gradually dip towards the Earth's surface at an ever-increasing angle until at the north geomagnetic pole itself it points vertically downwards. In other words, as you can see from Figure 13, the field direction gets steeper and steeper as you approach the north pole.

What will happen to the needle if you travel from the Equator to the south pole?

It will continue to point generally northwards and will again gradually change direction with respect to the Earth's surface. In accordance with the field direction, however, the needle will now point *upwards* at an ever-increasing angle until at the south geomagnetic pole it points vertically upwards.

(magnetic) inclination

The angle that the needle makes with the horizontal is called the *magnetic inclination* and is regarded as positive if the north pole of the needle dips below the horizontal and negative if it rises above the horizontal. With the simple geocentric axial dipole in Figure 13 the inclination is positive everywhere in the northern hemisphere and negative everywhere in the southern hemisphere.

In practice, inclination is usually measured using a compass needle that is mounted on a horizontal pivot or axis and is therefore constrained to move in the vertical plane. Indeed, you may make a rough measurement of inclination by turning your Home Experiment Kit compass vertically and setting the plane of the needle in the plane of the magnetic meridian.

What is the approximate inclination at your location?

You should find that the needle points downwards towards the north at an angle of 50–60°.

Now let us return to the situation shown in Figure 2 where the Earth's dipole is still geocentric but is no longer axial. One consequence of the slope of the dipole with respect to the rotational axis is that the geomagnetic and geographic poles no longer coincide. The points at which the dipole axis cuts the Earth's surface

(i.e. the geomagnetic poles) lie at 79° N, 70° W (north geomagnetic pole) and 79° S, 110° E (south geomagnetic pole).

Imagine yourself at the Equator again with your completely free compass needle, and imagine again your northward walk.

What will happen to the needle?

First, while you are at the Equator the needle will generally not lie horizontally. As you can see from Figure 2, the equator of the magnetic field, around which a compass needle will lie horizontally, no longer coincides with the geographic equator except at one point on each side of the Earth. Only at these two points on the geographic equator will the compass needle lie horizontally. Likewise, at the geographic poles the needle will no longer point vertically; it will do so at the geomagnetic poles which no longer coincide with the geographic poles. In other words, as you move from the geographic equator to the north geographic pole the inclination of the field will change, but not quite in the way it changed in Figure 13.

But will a horizontally constrained needle still point due (geographic) north?

No it will not. It will point due geomagnetic north (i.e. towards 79° N, 70° W) which is now generally different from due geographic north. In other words, the needle will make an angle with the geographic north direction. This angle is called the *magnetic declination* and is reckoned as °E or °W of true, or geographic, north.

(magnetic) declination

With the magnetic dipole axis oriented with respect to the geographic axis as in Figure 2, where will the declination be zero?

It will be zero if you happen to be on longitudes 70° W or 110° E. If you are on either of these longitudes, you, the north geographic pole and the north geomagnetic pole lie in the same line. A needle pointing due geomagnetic north will thus automatically point due geographic north as well.

Declination and inclination are just two of the *magnetic elements*—a set of quantities and angles that allow both the strength and directions of a magnetic field to be defined.

magnetic elements

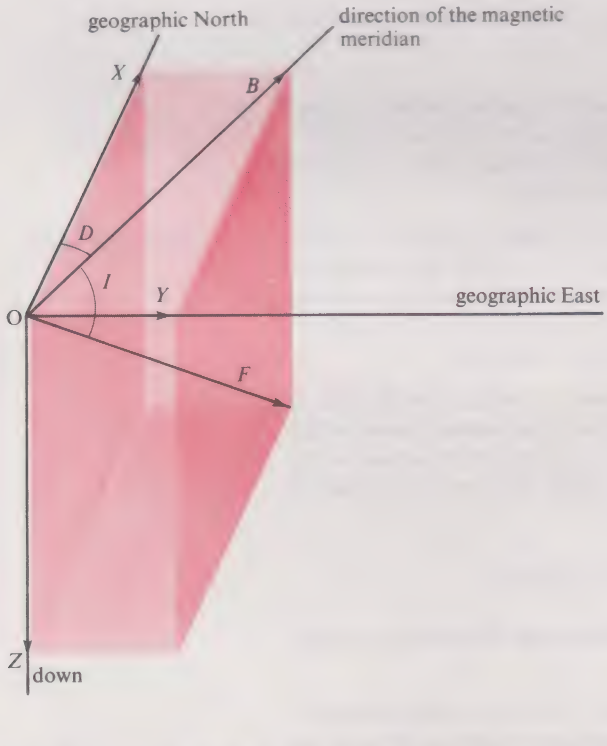


FIGURE 14 The magnetic elements.

Suppose that the magnetic field at any point O on the Earth's surface has a strength F and is directed as shown in Figure 14. F is a quantity with both a

strength and a direction. In Figure 14 the line marked F is thus in the direction of the magnetic field at O and has a length which is proportional to the strength, or magnitude, of the field.

A compass needle at O, free to rotate in the horizontal plane, will come to rest along B, the horizontal component of F. In other words, B is the direction of the magnetic meridian. The angle between B and geographic north is therefore the declination (D). Also, the angle that F makes with the horizontal is the inclination (I).

F may also be regarded as equivalent to X, Y and Z, the three components of the field acting, respectively, along true (geographic) north, along geographic east and vertically. X, Y and Z are regarded as positive if in the directions shown in Figure 14, and negative if in the opposite directions. In Figure 14 the lengths of X, Y and Z are proportional to their magnitudes.

The magnetic elements comprise X, Y, Z, B, F, D and I. They are used to describe magnetic fields, although all seven elements need not be specified. There are simple trigonometrical relationships between the elements which enable all seven to be determined from just three. For example, if X, Y and Z are specified or measured, it is possible to determine F, B, D and I by calculation from them.

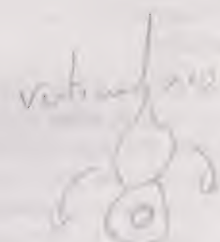
You should really master the geomagnetic elements before you proceed further, for we are now going on to describe the Earth's present and past magnetic fields in terms of one or more of the elements.

To summarize Section 3.1: At a few places on the Earth's surface the geomagnetic field points vertically upwards or downwards and at a few other places it points perfectly horizontally. At most places, however, it points neither exactly vertically nor exactly horizontally but in some intermediate direction. In Britain, for example, the field is directed downwards at an angle of 50°–60° below the horizontal and roughly northwards. The angle the field direction makes with the horizontal is called the magnetic inclination and is regarded as positive if the field points downwards and negative if the field points upwards. (In Britain, therefore, the inclination of the field is +50° to +60°.) The angle (usually small) between the field direction and geographic north is called the magnetic declination and is usually reckoned east of geographic north.

3.1.1 Objectives of Section 3.1

(a) You should now be familiar enough with the magnetic elements to be able to illustrate them diagrammatically and to recognize whether statements made about them are true or false.

(b) You should also be familiar with the meanings of the few new terms introduced in Section 3.1, namely, magnetic elements, geocentric, axial, (magnetic) declination and (magnetic) inclination.



SAQ 5 (*Objectives (a) and (b)*)

Which of the following statements are true and which are false?

(a) The declination of the geomagnetic field at a point on the Earth's surface is the angle between geographic north and the direction of the magnetic meridian passing through that point.

(b) The inclination of the geomagnetic field at a point on the Earth's surface is the angle between the direction of the geomagnetic field and the vertical.

(c) If a compass needle mounted on a vertical axis points north-east, the declination at the location of the needle is 45° E of north.

(d) If a compass needle mounted on a horizontal axis points upwards at an angle of 20° from the vertical, the inclination at the location of the needle is +70°.

(e) For a purely dipolar geomagnetic field sloping at 11° to the Earth's rotational axis, a completely free compass needle will point vertically downwards at the north geographic pole.

(f) For a geocentric axial geomagnetic field the directions of the magnetic meridians are lines of geographic longitude.

3.2 What is the Earth's magnetic field like now?

The question we shall try to answer in this Section is: what can be said about the Earth's present field from direct observations and analysis of those observations? Later on we shall examine how the geomagnetic field has changed with time, both during the very recent period and during the many millions of years which preceded it; but for the moment we shall concentrate on the present.

The simplest way of illustrating the features of the present field is to combine the measurements from all over the world into a series of magnetic maps, one map for each of the magnetic elements. If the experimental points were simply to be plotted on a world map, all we would see would be a hotch-potch of points which would obscure any regular pattern there might be. Instead, therefore, it is better to plot the magnetic elements as 'contour' lines joining points on the Earth's surface at which a given magnetic element is the same. Such maps are called *isomagnetic charts*. Lines joining the points at which the declination values are equal are called *isogonic lines*, or simply *isogonics*, and thus give rise to an *isogonic chart*. Similarly, lines of equal inclination are called *isoclinic lines* or *isoclinics*. Isomagnetic lines for the other elements do not have special names, but the principles behind their construction are the same.

isomagnetic charts
isogonic lines (isogonics)
isogonic chart
isoclinic lines (isoclinics)

It is not necessary to show all seven of the isomagnetic charts here; but to give you an idea of what the Earth's field looks like plotted this way, Figures 15 and 16 show the charts of equal declination, D, and equal geomagnetic field strength, F, for the year 1955.

Looking at these maps, you will probably conclude that there is little regularity about the geomagnetic field at all. To be sure, there is a pattern of sorts; but what can be deduced from it? Does the geomagnetic field plotted in this way really bear any resemblance to the field produced by a magnetic dipole, for example? One way in which we could proceed to test this idea would be to assume that the Earth contains a magnetic dipole at its centre, work out what sort of field this would produce at the Earth's surface and compare this with the observed field. When this is done it is, in fact, possible to show that the geomagnetic field is a dipole field to a first approximation. However, there is a limit to which such a simple model can be taken. To simulate the observed field more accurately, a more complex model must be used; and the one normally adopted is not a physical but a mathematical model.

The geomagnetic data from around the world are analysed into complex mathematical 'components', only one of which represents a dipole. What emerges from the analysis is a picture of the Earth's magnetic field that has the following characteristics:

1 All but a few per cent of the geomagnetic field is produced by processes inside the Earth: that is, most of the field is of internal origin, and is often called the *internal field*. The rest of the field we observe at the Earth's surface is of external origin (the *external field*), that is, it is produced by effects above the Earth's surface. Most of the external field is probably produced in the upper atmosphere. The external field is comparatively unimportant, and we will be concerned no further with it here. But we shall return to the question of where the main internal field is produced when we consider its origin.

internal field
external field

2 The Earth's field is mainly dipolar. This does not necessarily mean that the field is produced by a bar magnet in the Earth but only that, whatever the origin of the field is, the shape of the field is very similar to that of a bar magnet. However, the real processes that produce the dipole field of the Earth are probably extremely complex and difficult to visualize. For this reason it is convenient, for purposes of representation, to *imagine* a dipole in the Earth. This is known as the *geomagnetic dipole*.

geomagnetic dipole

3 The geomagnetic dipole lies at the centre of the Earth (i.e. it is geocentric), but does not lie along the rotational axis (i.e. it is not axial). As we have already noted, the geomagnetic dipole slopes at 11° to the rotational axis, giving geomagnetic pole positions at 79° N, 70° W and 79° S, 110° E. Moreover, the north geomagnetic pole corresponds to the south pole of the geomagnetic dipole itself, and vice versa (Section 2.2).

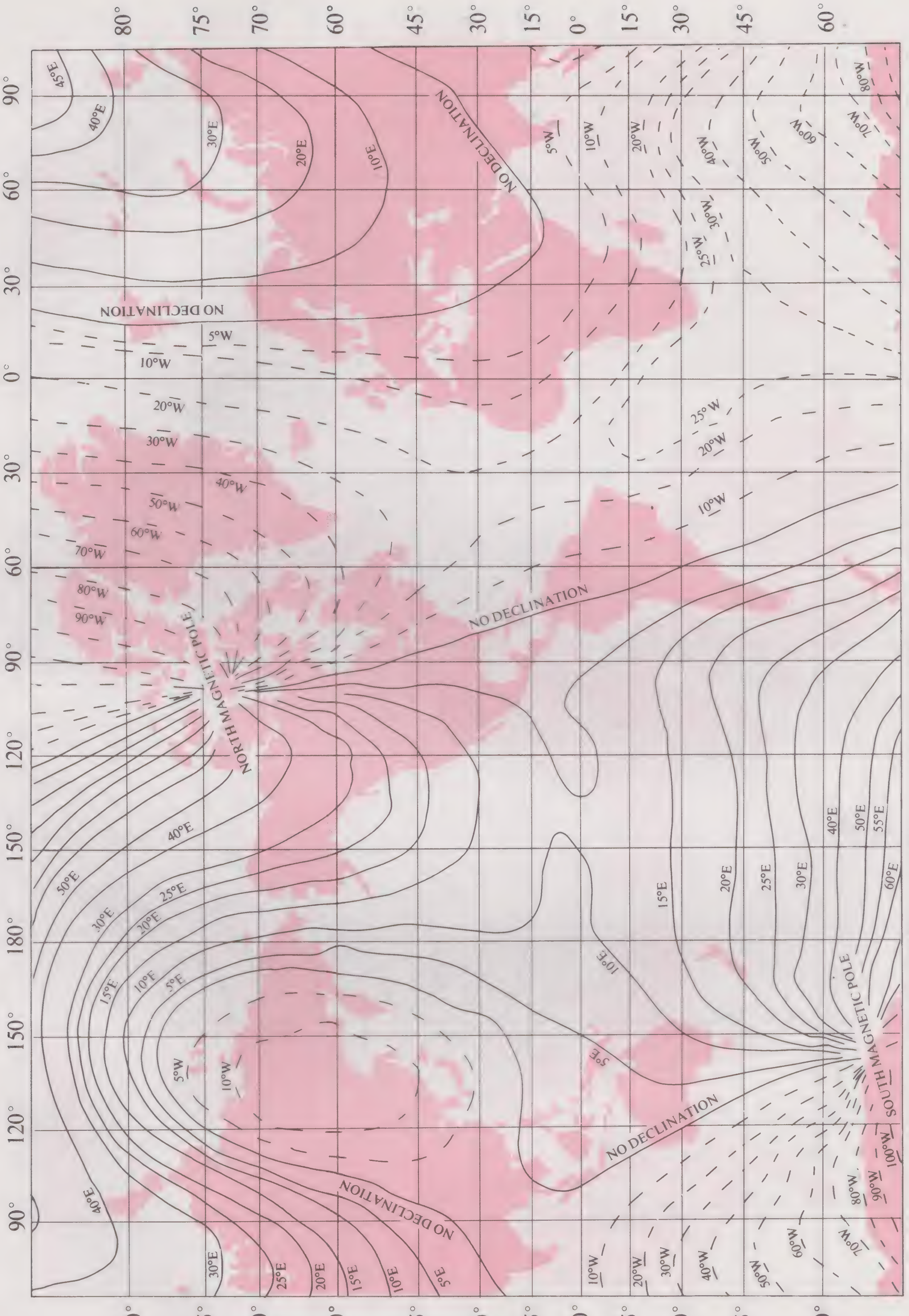


FIGURE 15 Isogonic chart for the year 1955. (Note that the magnetic poles depicted here are the magnetic dip poles.)

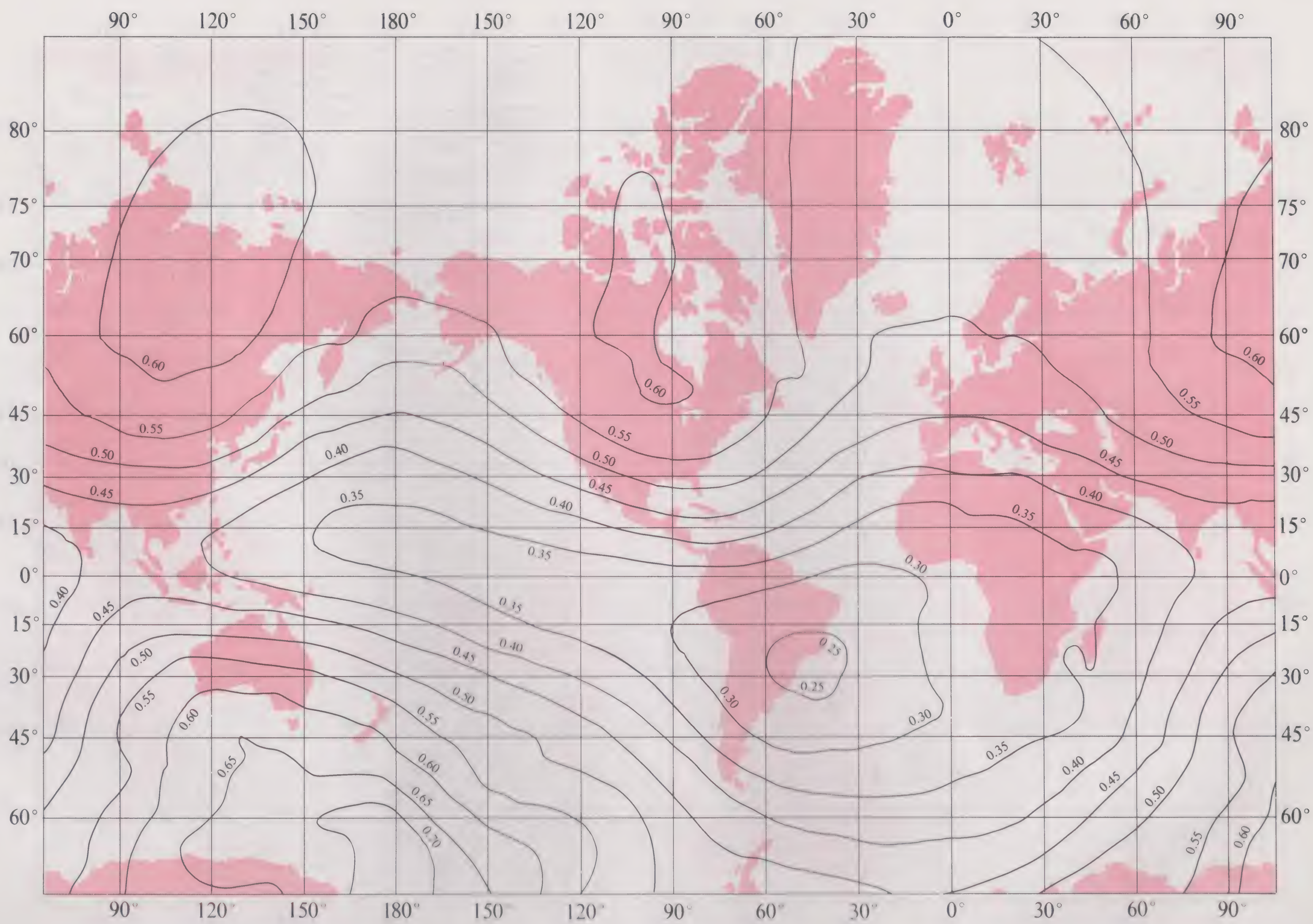


FIGURE 16 The strength (F) of the geomagnetic field for the year 1955. The units are 10^{-4} T (tesla).

4 If the geomagnetic dipole were the only component of the Earth's magnetic field, the strength of the geomagnetic field at each geomagnetic pole would be 0.62×10^{-4} T and around the geomagnetic equator would be 0.31×10^{-4} T. (T stands for 'tesla', the unit of magnetic field strength. You do not need to understand exactly how a tesla is defined; but for comparison with other fields later in this Unit you should remember the numerical values in this paragraph.)

5 In fact, the geomagnetic dipole is not the only component present. In addition to the dipole field there is also a *non-dipole field* which is irregular. It is this field which accounts for most of the irregularities on the isomagnetic charts. The non-dipole field is superimposed on the dipole field; and if the latter is subtracted mathematically from the total field we are left with the pure non-dipole field.

non-dipole field

Or to explain it another way:

Suppose that the strength and direction of the magnetic field are measured at a particular point on the Earth's surface. Call this measured value H_m.

Then suppose that the strength and direction of the magnetic field at the same point are calculated on the assumption that the Earth's field is exactly that of a geocentric dipole. Call this calculated value H_d.

We find that H_m and H_d are generally not the same, either in magnitude or direction. Let the difference between H_m and H_d be denoted by H_n. Then H_n is what is meant by the non-dipole field. It is simply that part of the actual magnetic field that cannot be accounted for by assuming that the Earth's field is entirely dipolar. We shall return to this point in Section 5.3 when we consider the possible origin of the Earth's magnetic field.

In the meantime you should look at Figure 17 (p. 26) in which the Z (vertical) component of the non-dipole field for 1965 is plotted. The magnetic elements for the non-dipole field may be contoured onto a world map in this way just as the magnetic elements of the total field. If you examine Figure 17 carefully you will see that the non-dipole field forms a series of high (positive) and low (negative) 'centres'. Thus, for example, just off the west coast of Africa there is a low centre which reaches -160×10^{-7} T, whereas over China there is a high centre which reaches $+180 \times 10^{-7}$ T. These extremes compare with the dipole field whose strength varies from about 310×10^{-7} T (0.31×10^{-4} T) at the Equator to 620×10^{-7} T (0.62×10^{-4} T) at the poles. You can see, therefore, that in some areas the non-dipole field can be quite a high proportion of the total. On average, however, the non-dipole field is only about 5 per cent of the total.

Where have you seen 'centres' of this type before?

If you look back at Figures 15 and 16 you will see that the 'centres' are reflected there also. They are not in the same places because we are now looking at the effect of the dipole field as well; but it is clear that the non-dipole field has made its mark.

6 If the geomagnetic field were entirely dipolar, the inclination (I) of the dipole field would be $+90°$ (that is, vertically downwards) at the north geomagnetic pole and $-90°$ (vertically upwards) at the south geomagnetic pole. But when the inclination is actually measured at the geomagnetic poles, it is found not to be 90°.

Can you see why?

This is because at the geomagnetic poles there is also a non-zero component of the non-dipole field. The inclination at the geomagnetic poles is the net result of the 90° dipolar inclination and the non-dipole inclination.

However, there are points at which the dipole and non-dipole fields just balance in such a way that the net inclination is vertical. These are called the *magnetic dip poles*. The north magnetic dip pole is at about 75° N, 101° W; and the south magnetic dip pole is at about 67° S, 143° E. The dip poles are thus not antipodal. This is because the non-dipole field is irregular and very different in each hemisphere. The non-dipole field bears no regular relationship to either latitude or longitude; and so neither do the points at which the dipole and non-dipole inclinations cancel.

magnetic dip poles

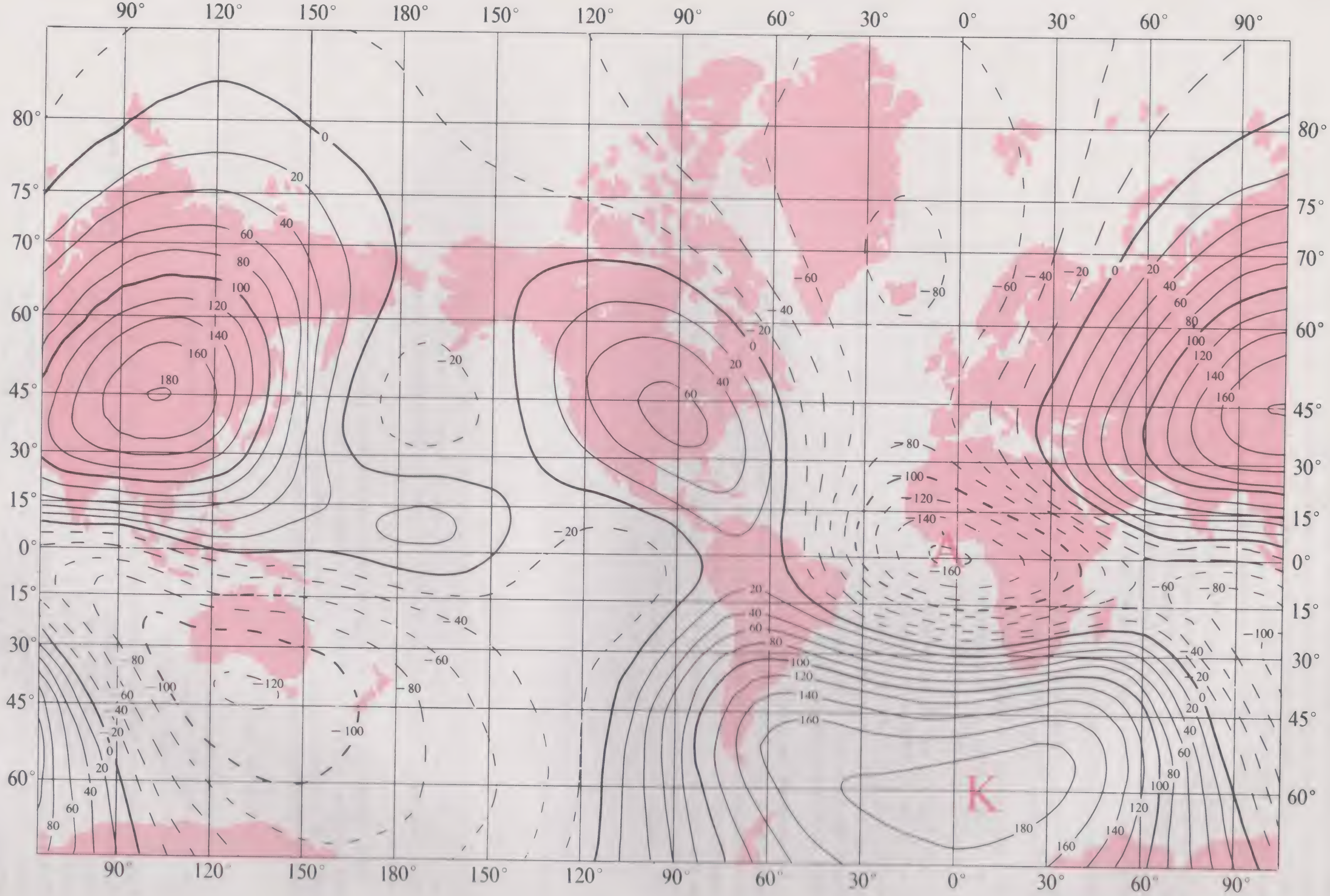


FIGURE 17 The Z component of the non-dipole field for 1965. The units are 10^{-7} T.

3.2.1 Objectives of Section 3.2

(a) Now that you have completed Section 3, you should be able to use the following terms correctly and/or recognize whether or not they are being used correctly: isomagnetic charts, isogonic lines (isogonics), isogonic chart, isoclinic lines (isoclinics), internal field, external field, geomagnetic dipole, non-dipole field, magnetic dip poles (north magnetic dip pole, south magnetic dip pole).

(b) You should also be able to describe and answer questions on the characteristics of the Earth's magnetic field as it is now.

SAQ 6 (*Objectives* (*a*) *and* (*b*))

Arrange the following components of the geomagnetic field in order of magnitude, beginning with the strongest:

(a) non-dipole field

(b) dipole field

(c) external field

SAQ 7 (*Objectives* (*a*) *and* (*b*))

Which of the following statements are true and which are false?

(a) An axial dipole is a dipole aligned along the Earth's rotational axis.

(b) The geomagnetic dipole is axial at the present time.

(c) Most of the magnetic field observed at the Earth's surface is produced by processes outside the Earth.

(d) The north and south geomagnetic poles are antipodal.

(e) The north geomagnetic pole is closer to the north pole of the geomagnetic dipole than to the south pole of the geomagnetic dipole.

(f) At the north geomagnetic pole the inclination of the Earth's magnetic field is $+90°$.

(g) The strength of the geomagnetic field produced by the geomagnetic dipole at the geomagnetic poles is 0.62×10^{-4} T (tesla).

(h) The north and south magnetic dip poles are antipodal.

SAQ 8 (*Objective* (*b*))

Figure 18 is a map of the world divided into rectangles, each of which may be identified by a letter and a number (for example, D6). Identify which rectangle(s) each of the following falls into:

(a) The north geomagnetic pole.

(b) The south magnetic dip pole.

(c) The centre of an area where the strength of the geomagnetic field is below 0.25×10^{-4} T.

(d) Two southern hemisphere continental areas in which the declination is 20° W.

(e) An area where the Z component of the non-dipole field reaches -160×10^{-7}T.

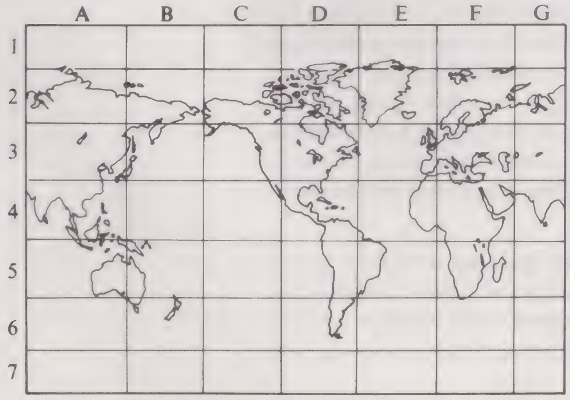


FIGURE 18 Map for SAQ 10.

4 Changes in the Earth's magnetic field

4.1 The period of direct observation

In 1635, Henry Gellibrand presented his discovery that between 1580 and 1634 the declination at London had changed from 11.3° E to 4.1° E. This was the first time that anyone had noticed that the Earth's magnetic field was not static, although it has to be admitted that the only magnetic elements that had ever been measured up to that time were declination and inclination, and that these early measurements were hardly the ultimate in accuracy. Subsequent observers found, especially after the more systematic measurements were begun early in the nineteenth century, that all the magnetic elements change with time. These changes are known as *secular variations* ('secular' as used here merely means 'time').

secular variations

Since 1838, when Gauss carried out the first mathematical analysis of the geomagnetic field, the field has been under observation almost continuously, and has been the subject of many subsequent analyses. These observations and analyses have enabled geophysicists to plot the changes that have taken place. What we shall do, then, is to summarize, with the aid of diagrams, what has been happening to the Earth's field over the past century or so.

4.1.1 The geomagnetic dipole

Throughout the whole of the period covered by direct observation, the geomagnetic field has been predominantly dipolar; but the axis of the dipole has moved a little. During the past 130 years or so the latitude of the north geomagnetic pole has remained roughly constant at about 79° N; so the angle between the geographic and dipole axes has remained more or less steady at 11°. But during this period the longitude of the north geomagnetic pole has changed from about 64° W to about 70° W—an average rate of change of about 0.042° longitude a year.

> Would you deduce from the information in the last paragraph that the north geomagnetic pole moves around the north geographic pole at a constant latitude of about 79° N?

It is important to realize that at this stage we can say *absolutely nothing definite* about the motion of the geomagnetic pole before the nineteenth century. Before the period of direct observation it may have been moving as it has done over the past 130 years or so, or it may not. We can, however, say two things. First, *if* the pole has been moving in the way described here it would have taken about 10^4 years to make a complete revolution. Second, we can make a reasonable speculation about the past behaviour of the geomagnetic dipole. Thus it is reasonable to expect that the dipole would lie along the Earth's rotational axis because this is the only unique axis in the Earth. If you think about it you will see that any axis drawn through the centre of the Earth is no more likely to be the right one than any other—*except* the rotational axis. In other words, all the axes are indistinguishable except the one that passes through the geographic poles. Yet it is clear from observations that, over the past 130 years or so, the geomagnetic dipole axis has not coincided with the rotational axis and thus that the geographic and geomagnetic poles have not been coincident. If our original speculation is correct, therefore, we might infer that the geomagnetic pole wanders about so that *averaged over long periods of time* the geomagnetic and geographic poles coincide. We would thus not expect the dipole to have been always inclined at 11° to the rotational axis, though again we have no evidence from direct observation to say otherwise.

The change in dipole orientation may not have been spectacular, but the change in the strength of the field produced by the geomagnetic dipole certainly has. During the period of direct observation the geomagnetic field strength has been decreasing more or less linearly at a rate of about 5 per cent per century all over the Earth's surface (see Figure 19).

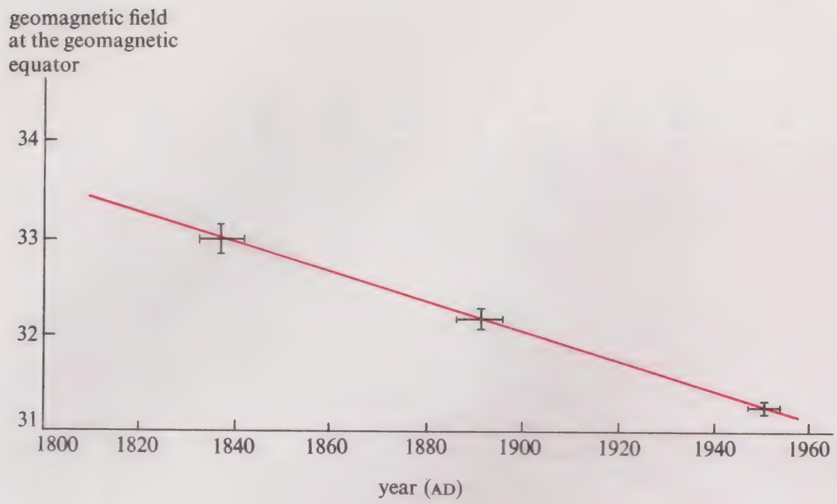


FIGURE 19 Change in the geomagnetic field strength (F) at the geomagnetic equator. Units: 10^{-6} T. The points are average values of all determinations within the 50-year intervals 1815–1865, 1865–1915 and 1915–1965, respectively. The error bars represent the standard errors of the means.

4.1.2 The non-dipole field

Figures 20a and 20b show, respectively, the Z (vertical) component of the non-dipole fields for 1965 and 1835. You have met Figure 20a before as Figure 17, but it is repeated on p. 28 so that you can easily compare the two parts of Figure 20.

Can you spot any significant differences between Figures 20a and 20b?

In a broad way the non-dipole fields for 1835 and 1965 are similar, but there are some important differences. Look first at the 'centre' marked A on each chart. In 1835 its magnitude was greater than 80×10^{-7} T and it lay to the east of Africa. But by 1965 its maximum value had increased to over 160×10^{-7} T and it had moved westward to the west of Africa. Then look at the centre marked K. Between 1835 and 1965 it grew by over 20×10^{-7} T, a somewhat smaller rate than centre A; it again moved westward, but only very slightly; and the whole region between the extreme $Z = 0$ lines expanded somewhat. Then look at centre R on the 1835 chart. By 1965 it had completely disappeared. If you have time, take a look at what happened to some of the other centres.

These examples illustrate some very important properties of the non-dipole field. This field is continuously changing. On average the whole field is drifting westward at a rate of about 0.2° longitude a year. This would seem to imply that if it were to persist long enough it would move right around the world in about 1 800 years. In fact, it does not persist in one form for that long. The centres are continuously changing—growing, diminishing, expanding, contracting and disappearing and reappearing—and they do all these things with periods of the order of 10 to 10^3 years. The apparent periodicity of the dipole movement, on the other hand, was, if you recall, of the order of 10^4 years. The non-dipole field is thus changing at a rate which is at least an order of magnitude higher than that of the dipole field.

4.2 Indirect measurement of the past geomagnetic field

Now we have seen how the Earth's magnetic field has behaved over the past 130 years or so—but how little we really know! And how many questions are raised by our knowledge of the field over so short a period of time! Has the Earth's field always been dipolar? If so, has it been on average an axial dipole, that is, one aligned with the geographic axis? Or is the axial dipole hypothesis merely a product of wishful thinking—part of our attempt to make nature conform to our own intellectual over-simplifications? Has the geomagnetic field strength always been decreasing? Are there any long-term variations of the field that could not possibly be determined from direct observation over a mere century or so? For that matter, how long has the Earth possessed a magnetic field?

Twenty years ago none of these questions could have been answered. Today they can be, at least in part, thanks to a remarkable discovery actually made in the nineteenth century but only developed to any useful degree over the past 20 years.

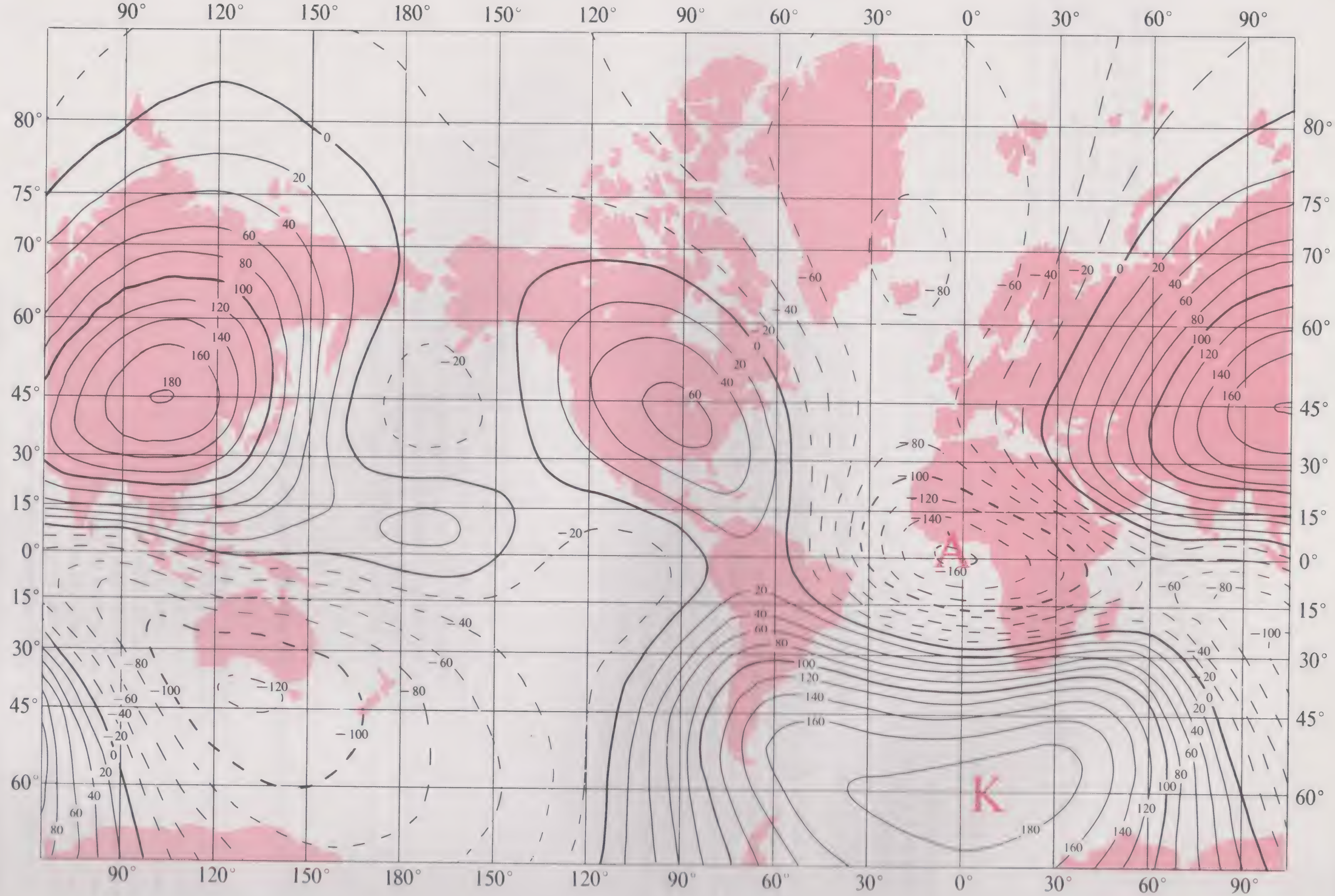


FIGURE 20a The Z component of the non-dipole field for 1965. Units 10^{-7} T.

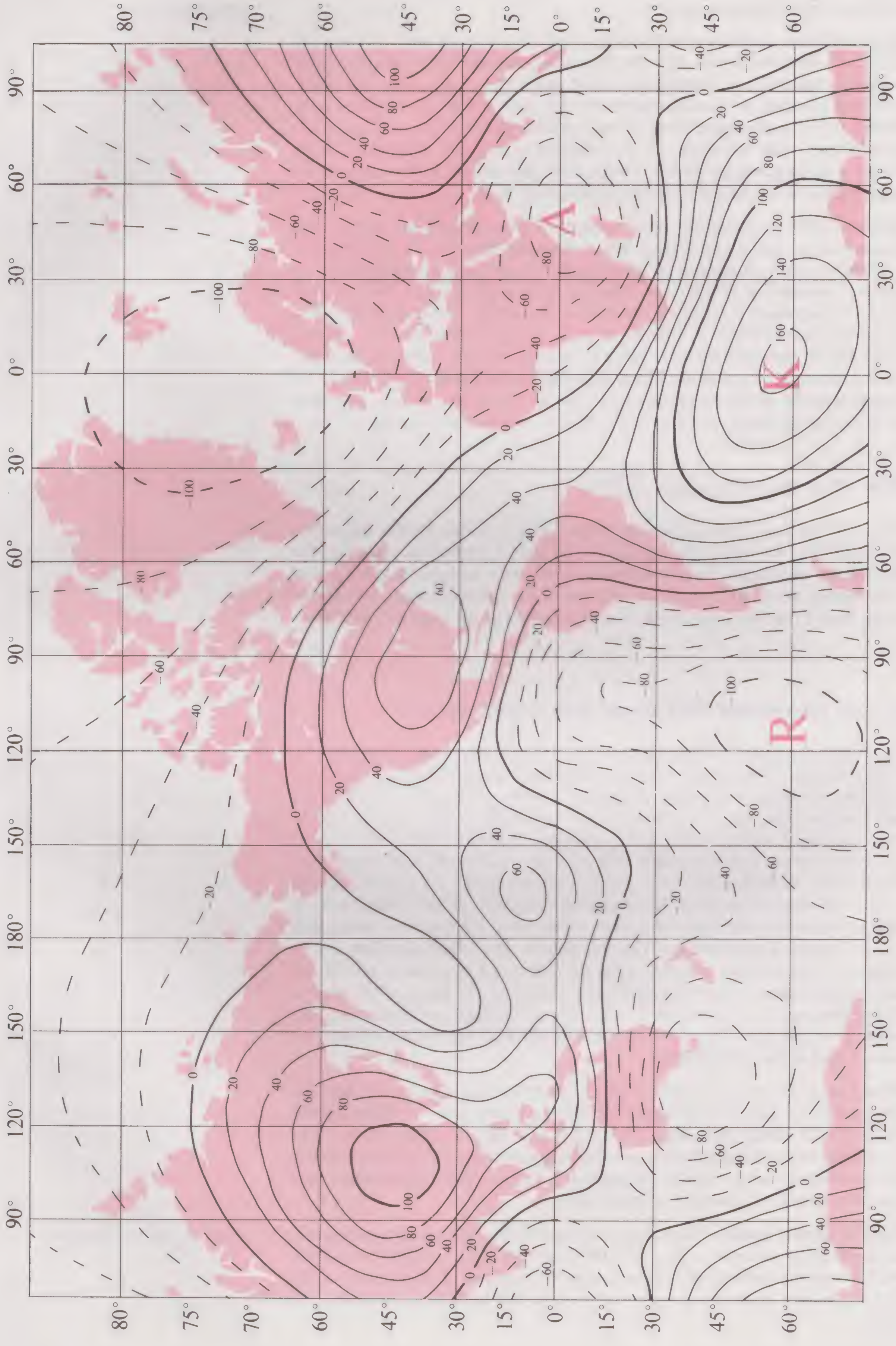


FIGURE 20b The Z component of the non-dipole field for 1835. Units: 10^{-7} T.

And that is that many rocks record and preserve the direction and magnitude of the geomagnetic field at the time they are formed. The study of the magnetization of rocks is called *palaeomagnetism*.

palaeomagnetism

Almost all rocks contain a small quantity (typically a few per cent) of iron compounds. In the types of rock most used for palaeomagnetic work—igneous rocks* (especially basalts) and sedimentary rocks* (especially sandstones)—the important iron minerals are usually magnetite or hematite, both of which are compounds of iron and oxygen, though there is often titanium in place of some of the iron. When a rock is formed, the iron minerals in it become magnetized in the direction of the geomagnetic field. Furthermore, the strength of the magnetism is proportional to the magnitude of the geomagnetic field.

However, rocks are extremely weak magnets. A piece of rock having the same dimensions as, say, a toy magnet has a magnetic field that is usually many hundreds or even thousands of times weaker. Very sensitive instruments are therefore required to measure the magnetic fields rocks produce. On the other hand, the magnetism is extremely stable. Once magnetized, a rock can preserve its magnetism for hundreds of millions of years (compare this with toy magnets, which can be demagnetized very easily). Obviously it is quite impossible to measure the ancient geomagnetic field directly; but all over the world there are rocks of all ages with the ancient fields 'fossilized' into them. And there they lie, waiting to be measured, to divulge the information they have stored for so long.

4.3 How old is the geomagnetic field?

The oldest rock known to possess an original magnetization (that is, magnetism taken up when the rock was formed) is more than 2 600 million years old. The implication, therefore, is that the Earth has possessed a magnetic field for at least 2 600 million years. By comparison, the age of the Earth is about 4 500 million years (Ma). (You will learn about the evidence for this estimate in Unit 26.)

4.4 Has the geomagnetic field always been mainly dipolar?

Once the declination (D) and inclination (I) of the ancient geomagnetic field at a given site have been obtained from measurement of a rock's magnetization, it is possible to calculate the ancient geomagnetic pole position, or palaeomagnetic pole position. However, in order to do this we must assume the field to be dipolar. Now, you might well ask what use it is to assume the field to be dipolar when we are trying to prove that very point! But this is not quite so silly as it seems. Look at it this way. In dealing with rocks from all over the world, it is quite impossible to test the dipole hypothesis by comparing directions of the ancient field at different sites because, even for a pure dipole field, the direction varies with position on the Earth's surface. The only way in which field directions can be compared is to calculate a parameter which is common to *all* directions. This is conveniently taken to be the principal axis (and hence the poles) of the original global geomagnetic field, irrespective of whether that field was dipolar or something more complex. We choose to try a dipole field first mainly because the present field is essentially dipolar.

What would we expect to happen if we are right? If we are right, and the field at a given point in time was dipolar, all rocks of that age, irrespective of their positions on the Earth's surface, should give the same palaeomagnetic pole. However, if we are wrong, and we have calculated pole positions assuming a dipole field when in fact the field was more complex, all rocks of that age will not give a common pole but poles that are scattered all over the place.

What happens in practice? If you look at Figure 21 you will see *north palaeomagnetic pole positions* from rocks up to 7 000 years old. Before you go any further read the caption carefully so that you know the positions of the geographic pole and the present geomagnetic pole, and so that you understand what the plot means.

palaeomagnetic pole positions

* Igneous rocks are rocks that have cooled from volcanic lava; sediments were deposited as small particles.

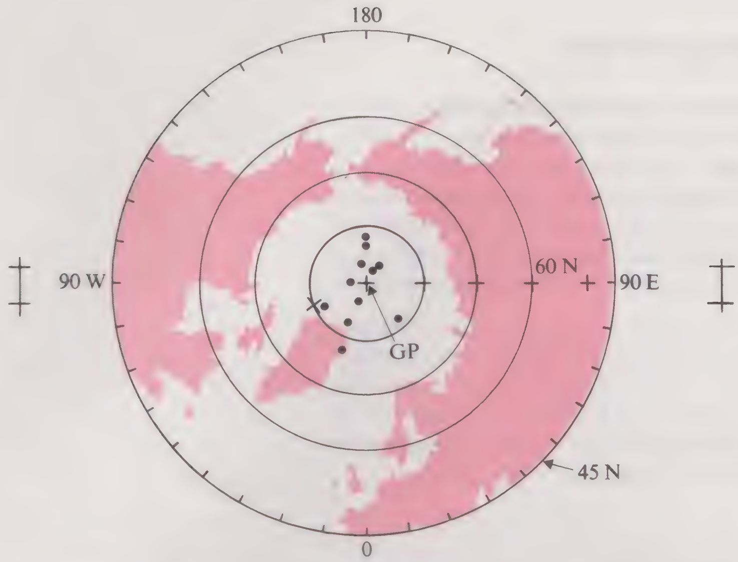


FIGURE 21 Palaeomagnetic north poles (●) at different points in time during the past 7000 years. Imagine that you are looking down on the Earth from a point directly above the north geographic pole (GP) which is therefore in the centre of the diagram. The poles are thus plotted exactly as you would see them, assuming they were marked in some way. The cross (×) is the position of the present north geomagnetic pole. Notice that the outer circle represents 45° N latitude; the area between that latitude and the Equator, which you would see from your vantage point, has been omitted for clarity. (*Note* Each of the palaeomagnetic poles shown is an average for many rock samples. In each case, therefore, any scatter there may be from the non-dipole field has been effectively removed.)

Now look at the palaeomagnetic pole positions. Your first impression may be that they *are* scattered all over the place. In fact, if you look closely you will see that they all lie within about 11° of the geographic pole, which is quite a small scatter when you consider that they could lie anything up to 180° of latitude away. So we can say that over the past 7 000 years the geomagnetic field has been mainly dipolar because all the pole positions are very close.

But notice something else. The poles are not scattered around the present geomagnetic pole but around the geographic pole.

What do you deduce from this?

There are several things we can deduce from this. First, the geomagnetic pole has not always been 11° away from the geographic pole, as it is at present, but has wandered around. Second, it has wandered around the geographic pole. Thus, on average, it has been an axial dipole. Third, the fact that its maximum deviation from the geographic pole is about 11° suggests that it does not usually wander much further than that. Last, because, when averaged over a period of 7 000 years or so, the dipole is axial, we can say that the period of the '*dipole wobble*' around the geographic pole is of the order of 10^4 years.

dipole wobble

If we were to plot similar diagrams for rocks up to several million years old, we should again see the effect of an axial dipole. For rocks older than that, however, the palaeomagnetic poles get further and further away from the geographic pole; and, moreover, the palaeomagnetic poles from different continents move away from the geographic pole in different directions. This and other evidence strongly suggests that the points of reference—the continents on which the rock samples were collected—have moved. The evidence, including palaeomagnetic evidence, for continental movements (*continental drift*) will be presented in much more detail in Units 6–7.

continental drift

But to return to the question of dipolarity: the point is that, if the continents have moved, it becomes impossible to test the dipole hypothesis directly. However, more sophisticated tests do show that most palaeomagnetic directions are consistent with an axial dipole, so that we can be fairly sure that the Earth's field has always been mainly axially dipolar.

4.5 Changes in the strength of the geomagnetic field

Rocks are not the only things that can be used for palaeomagnetic measurements. Over the past few thousand years, many civilizations in various parts of the world have produced artefacts, such as kilns, which have been baked to high temperatures. These, too, record the direction and magnitude of the geomagnetic field at the place and time at which they cooled down after being baked. Artefacts are particularly useful for investigations of the field over the past few thousand years because in many cases they can be accurately dated by archaeological methods.

Many such materials have been used to determine how the strength of the geomagnetic field has varied. Most of the data obtained have been used in constructing Figure 22. This curve shows that over the indicated period of time the geomagnetic field strength has been fluctuating with a period of the order of 10^4 years. You will see that the decrease in field strength over the past 130 years or so, also plotted in Figure 22, forms a small part of one fluctuation.

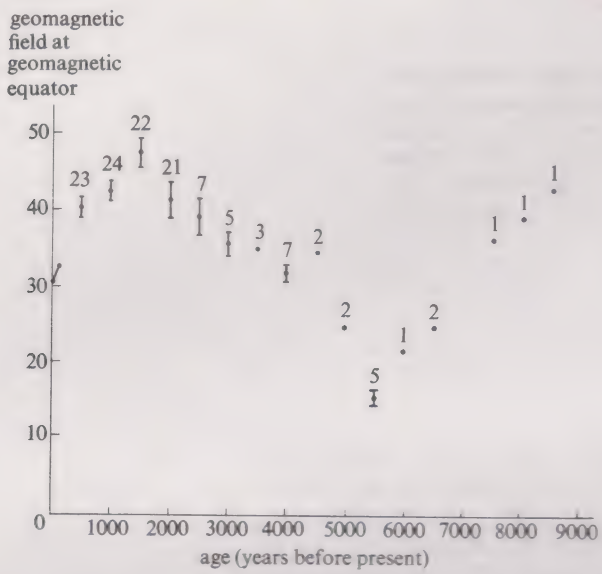


FIGURE 22 Change in the geomagnetic field strength at the geomagnetic equator for the past 8 000–9 000 years. Units: 10^{-6} T. The points are average values of all determinations within the 500-year intervals 0–500 years ago, 500–1 000 years ago, etc., respectively. The number of determinations averaged is shown above each point. The error bars are standard errors of the means, but have not been calculated where there are too few data to provide accurate values. The short bar on the left is the line from Figure 19.

It is not possible to extend these results back into geological time, because such well-dated materials closely spaced in time are not available. However, dipole fluctuations have probably been occurring throughout the whole period covered by the rock record.

4.6 Field reversals: an unexpected bonus

Soon after the first palaeomagnetic work was done, scientists made a completely unexpected discovery. Some rocks were reversely magnetized, that is, they apparently recorded not the direction of the geomagnetic field but precisely the opposite direction. In other words, as permanent magnets these rocks had their north and south poles reversed.

How could this be? There seem to be only two possibilities. Either the geomagnetic field was reversed at the time these rocks were formed (*field reversal*), or else some rocks possess some intrinsic property whereby they record the opposite field direction (*self-reversal*).

field reversal

self-reversal

How can we determine which is correct—field reversal or self-reversal? There are several ways of doing this; but one is of particular importance. If a rock is self-reversed, the self-reversal mechanism must depend upon some physical or

chemical property in the rock, a property which presumably some rocks would possess and some would not. Thus, if we take a large number of different types of rock, all of the same age, some are likely to be *reversed* (R) and some not. Non-reversed rocks are termed *normal* (N). If, on the other hand, field reversal is correct, all rocks of one given age will have the same polarity, because at a given point in time the geomagnetic field cannot be both normal and reversed.

reversed
normal

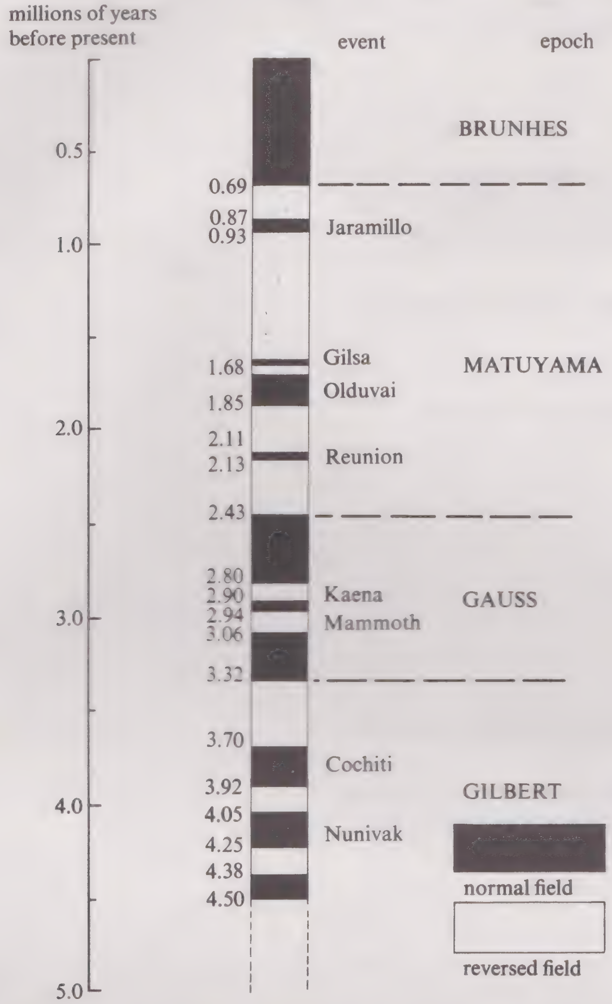


FIGURE 23 The polarity time-scale for the past 4.5 million years. Notice that both epochs and events have been given names. This scale may not yet be complete; many short events almost certainly remain to be discovered.

In fact, all rocks of a given age have the same polarity. This was proved in a beautiful piece of work carried out largely by Allan Cox and Richard Doell of the United States Geological Survey during the 1960s. What they did was to collect all the young rocks they could, measure their polarities and date them accurately. Because all rocks of the same age have the same polarity, Cox and Doell were able to build up a well-defined 'polarity/time scale' comprising epochs, periods of the order of one million years when the field was predominantly of one polarity, and events, shorter periods of opposite polarity within epochs (Figure 23). (Unfortunately, it is impossible to extend the polarity/time scale beyond 4.5 Ma ago, because the dating becomes too inaccurate to define the events properly.) Thus there is no doubt that reversely magnetized rocks are due to a geomagnetic field which has reversed many times in the past (Figure 24). Although it is not possible to plot a detailed polarity/time scale back beyond 4.5 Ma, reversed rocks exist throughout the whole rock record. Field reversal is thus a fundamental property of the geomagnetic field, and must, like all other properties we have discussed, be incorporated into any valid theory for the origin of the field.

But what is the origin of the field if there is no bar magnet at the Earth's centre? In Section 5 we shall take a look at other ways in which magnetic fields may be generated.

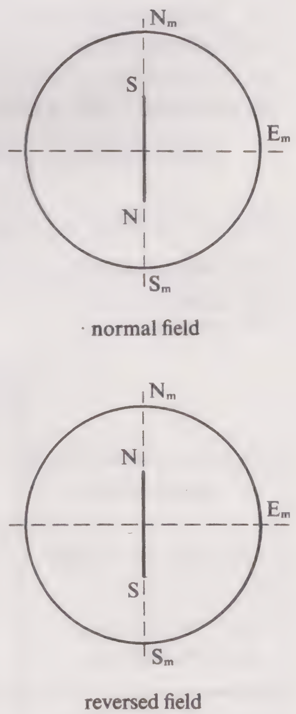


FIGURE 24 The normal and reversed geomagnetic fields.

4.7 Objectives of Section 4

(a) The new terms introduced in Section 4, and which you should now understand, are secular variations, palaeomagnetism, palaeomagnetic pole positions, dipole wobble, continental drift, field reversal, self-reversal, normal and reversed.

(b) The whole of Section 4 has been devoted to changes in the Earth's magnetic field, both those observed directly and those determined indirectly using rocks and artefacts. You should now be able to describe these changes either in words or diagrammatically.

SAQ 9 (*Objectives (a) and (b)*)

That part of the geomagnetic field produced by processes inside the Earth may be divided into two components, the dipole field (i) and the non-dipole field (ii). To which component(s) do the following expressions refer?

(a) Variations with time.

(b) An average rate of change of 0.042° longitude per year over the past 130 years or so.

(c) The westward drift of geomagnetic field 'centres'.

(d) Growth and decay with periods in the range 10 to 10^3 years.

(e) Constant latitude.

(f) A field strength of 0.15×10^{-4} T.

(g) 11° from the rotational axis.

(h) 0.2° longitude a year.

(i) A decrease of 5 per cent per century.

SAQ 10 (*Objectives (a) and (b)*)

Which of the following statements are warranted (i) and which are unwarranted (ii)?

(a) Direct observation of the geomagnetic field indicates that the north geomagnetic pole moves along 79° N latitude, taking about 10^4 years to make a complete revolution around the geographic pole.

(b) The Earth possessed a magnetic field 4 000 million years ago.

(c) The non-dipole field today looks just as it did about 1 800 years ago.

(d) The geomagnetic field has been constant in magnitude over the past few thousand years.

(e) Over the past 7 000 years the geomagnetic field has been predominantly dipolar and on average that of an axial dipole.

(f) The geomagnetic dipole has reversed many times in the past.

SAQ 11 (*Objectives (a) and (b)*)

In the table below, four geomagnetic phenomena and various characteristic time scales in years are listed. Tick the time scale(s) that correspond(s) to each phenomenon.

	(a) 1	(b) 10	(c) 10^2	(d) 10^3	(e) 10^4	(f) 10^5	(g) 10^6	(h) 10^7	(i) 10^8
(i) dipole wobble					✓				
(ii) non-dipole field		✓	✓	✓					
(iii) field reversals up to 4.5 Ma ago									
(iv) fluctuations in dipole field strength					✓				

SAQ 12 (*Objectives (a) and (b)*)

If you were asked to write a short essay on palaeomagnetism, which of the following items would you consider (i) relevant, and (ii) irrelevant?

(a) The Earth's external magnetic field.

(b) Magnetite and hematite.

(c) The oldest known rocks containing magnetism.

(d) Measurement of the present non-dipole field.

(e) The dipolarity of the Earth's magnetic field in the past.

(f) Self-reversal and field reversal.

5 The origin of the geomagnetic field

5.1 Forces between electric currents

Look at the two electrical circuits in Figure 25a. Each contains a battery and switch connected together by metallic wire which is a good conductor of electricity; and part of the wire (A) in one circuit runs close to part of the wire (B) in the other.

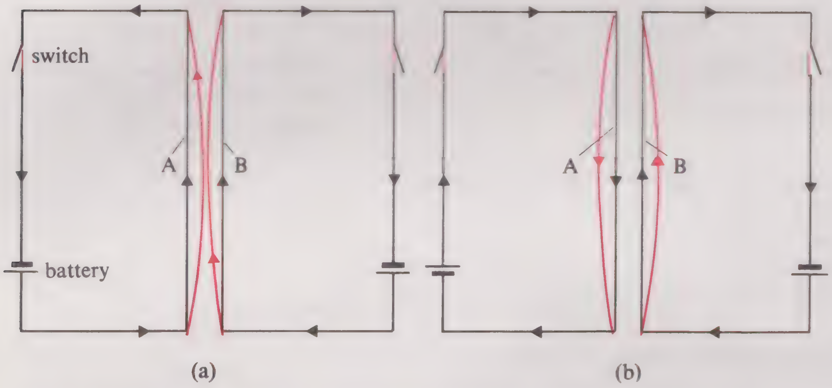


FIGURE 25 Circuits to demonstrate the forces of attraction and repulsion between current-carrying conductors.

These circuits may be used to demonstrate some very important results*:

1 When both switches are closed, the wires A and B are attracted towards each other. The force of attraction is present only when *both* switches are closed; open one and A and B will cease to attract.

2 When the connections to one of the batteries are reversed as shown in Figure 25b and the switches are again closed, the wires A and B are pushed apart; they now repel each other.

3 When the number of batteries in the circuits is increased, the forces of attraction and repulsion are also increased.

4 When the wires A and B are moved further apart the forces decrease.

These effects occur because when the switches are closed electric current flows around the circuits in the directions shown by the arrows. But what is electric current? Briefly, it is the flow of tiny particles, called electrons, which are one of the basic constituents of all matter and which have a property called charge. For present purposes it is necessary to know only that charge is something which, when in motion, produces a magnetic field. You will find out more about charge and how it is related to electricity in Unit 8; and you will learn more about electrons in Units 9–11.

5.1.1 Objective of Section 5.1

(a) You should now be able to predict the directions of the magnetic forces between straight current-carrying conductors. (The only new terms introduced in this section were electric current, electrons and charge—terms which we have decided not to define too closely at this stage.)

* These phenomena are shown in the TV programme associated with this Unit (TV 05).

SAQ 13 (*Objective* (*a*))

Figure 26 shows 6 pairs of wires, all drawn to the same scale. Decide whether the force between the members of each pair is one of attraction or repulsion.

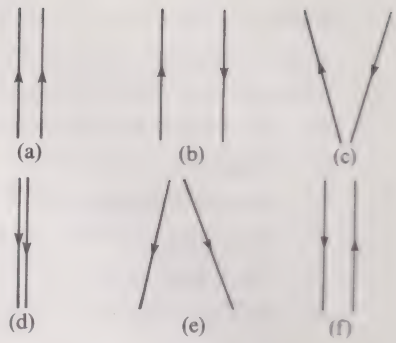


FIGURE 26 Diagram for SAQ 13.

5.2 Forces between electric currents and magnets

Look at the apparatus in Figure 27. There is an electrical circuit with a battery and a switch; and part of the circuit is a straight wire (CD) which passes down through a non-magnetic table. A small compass is placed on the table to the south of the wire, so the needle points towards the wire (i.e. towards the north) when the switch is open and no current is flowing in the circuit.

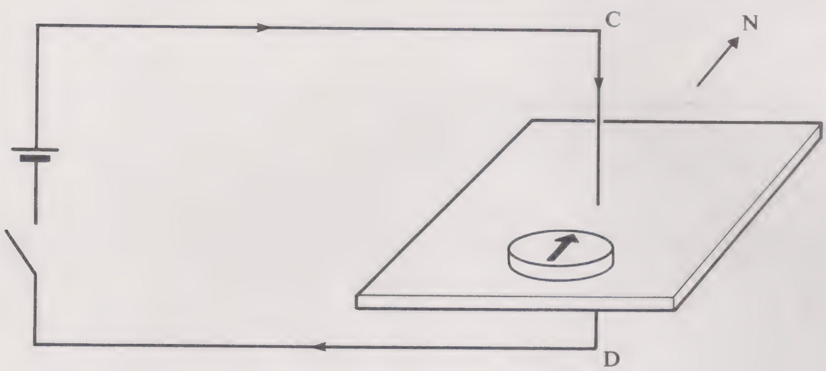


FIGURE 27 Apparatus for demonstrating and plotting the magnetic field around a straight current-carrying conductor.

But, when the current is switched on, the needle is deflected and ends up pointing westward. When the current is switched off again, the needle returns to its original position. If the battery connections are reversed and the current switched on again, the needle is again deflected; but this time it ends up pointing eastward. And when the current is switched off, the needle returns to pointing northward.

What do you conclude from the fact that the needle is deflected when the current is switched on?

Since a compass needle reacts to magnetic fields, the current-carrying wire CD must be producing a magnetic field.

By repeating the experiment with the compass in different positions around the wire, it is possible to plot this field just as you plotted the field from a bar magnet. This is shown in Figure 28. Whether the current is flowing up or down the wire the magnetic field is circular in shape, although when the current direction changes the magnetic field direction changes*.

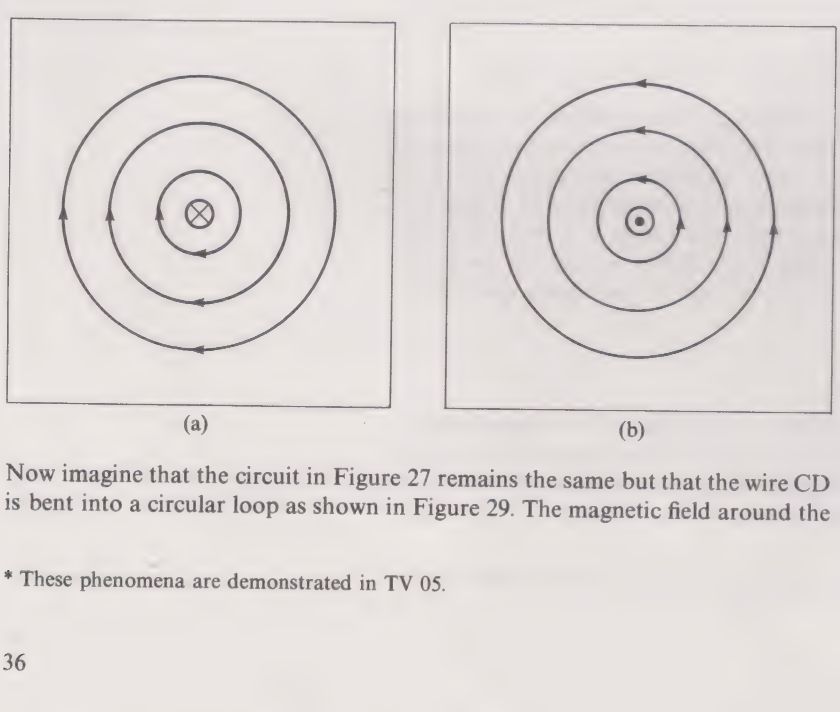


FIGURE 28 The directions of the magnetic fields around straight current-carrying conductors. The cross symbol in (a) is used to indicate that the current is flowing into the paper; the circular magnetic field is directed clockwise. The point symbol in (b) is used to indicate that the current is flowing out of the paper; the circular magnetic field is directed anti-clockwise.

Now imagine that the circuit in Figure 27 remains the same but that the wire CD is bent into a circular loop as shown in Figure 29. The magnetic field around the

* These phenomena are demonstrated in TV 05.

wire will still be circular but now the circular fields from each segment of the wire will interact. If you examine Figure 29 very carefully you should be able to see that in the plane of the loop the direction of the field is everywhere to the left on the inside and to the right on the outside when the current is in the direction shown*.

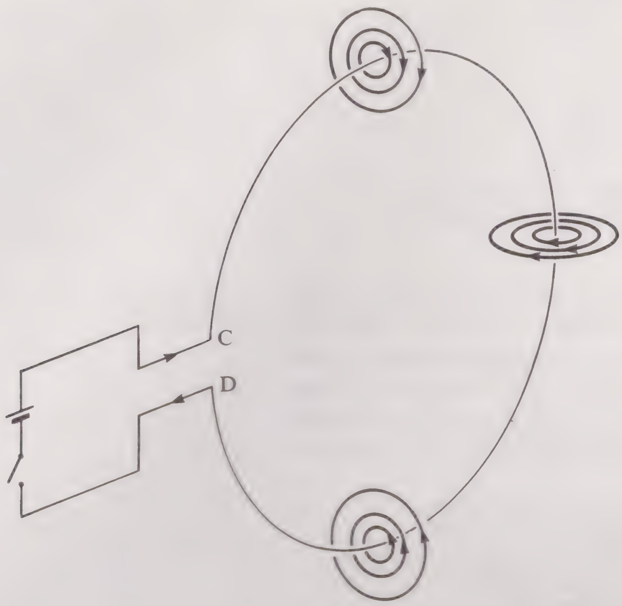


FIGURE 29 The circular magnetic fields around the segments of a current-carrying loop. The individual fields add up to produce the overall field shown in Figures 30 and 31.

If the current in the circuit in Figure 29 were reversed, what would happen to the directions of the magnetic field inside and outside the loop?

They would reverse also. In the plane of the loop the direction of the field would be everywhere to the right on the inside and to the left on the outside. The point is that, irrespective of the current direction, the circular fields round each segment of the loop reinforce each other to produce a magnetic field through the coil in a

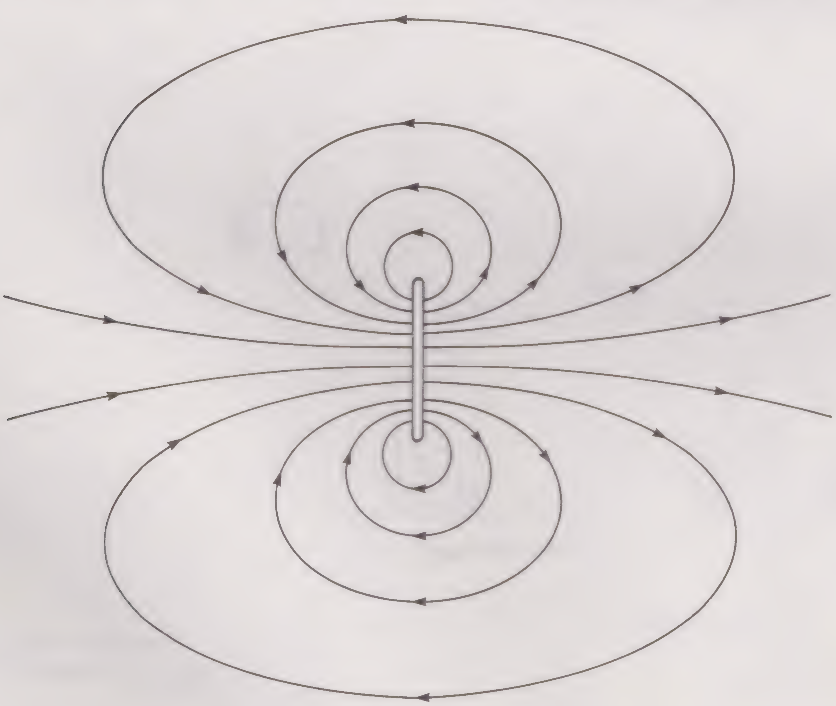


FIGURE 30 The magnetic field produced by a current-carrying loop. The loop is viewed edge on, and the current is flowing in the same directions as that in Figure 29. The field is plotted in two dimensions only—in the plane of the paper—although the loop does, of course, produce a three-dimensional field.

single direction. So that you can fix firmly in your mind the shape of the field through a loop, we give two further, and different, representations of it in Figures 30 and 31.

* These phenomena are demonstrated in TV 05.

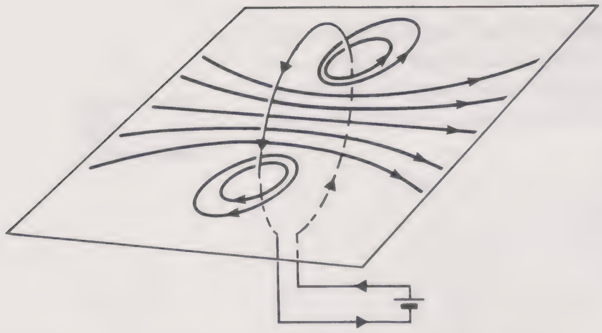


FIGURE 31 Another view of the magnetic field produced by a current-carrying loop. The field is again plotted in two dimensions only.

If, instead of just one loop of wire you could coil up the wire into many closely spaced loops, the current would go in the same direction around each turn of the coil; and each loop of current would produce an almost identical magnetic field (Figure 32). A coil like this would produce a stronger field than that of a single turn carrying the same current (ten times stronger if, for instance, the coil had ten turns), but a magnetic field of essentially the same shape as that of a single turn.

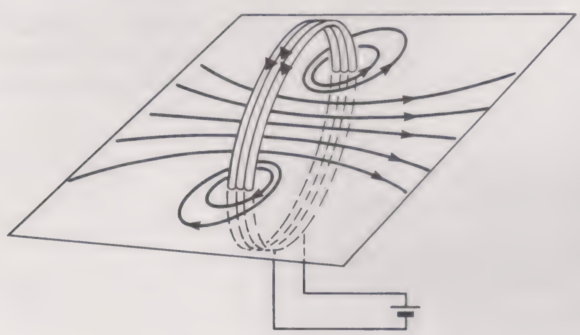


FIGURE 32 The magnetic field produced by a current-carrying coil. The field is plotted in two dimensions only, although it exists in three.

Now imagine another experiment, which is shown in Figure 33. This time a current-carrying coil is free to move up and down above a powerful bar magnet which is fixed. With the current switched off, the coil, which hangs from the arm of a balance, is just counterbalanced by the weight in the scale pan. But when the current is switched on the coil is pulled down towards the magnet; and when the current is switched off again the coil goes back to its original position*.

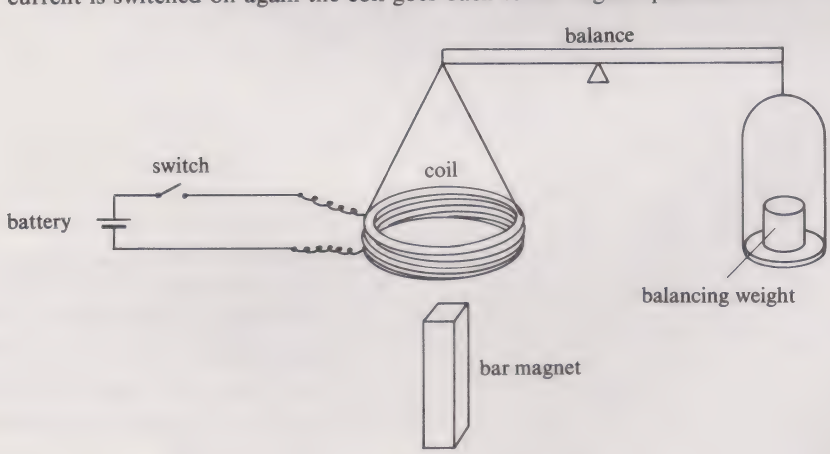


FIGURE 33 Apparatus for demonstrating the force between a bar magnet and a current-carrying coil.

Why is the coil pulled down towards the magnet?

When the current is switched on the coil produces a magnetic field. Since the reaction of this field to the field of the magnet is one of attraction, the coil must be

* This is demonstrated in TV 05.

presenting to the magnet a pole opposite to that at the upper end of the magnet. In other words, if the upper pole of the bar magnet is a north pole, the current in the coil must be flowing in such a direction as to produce a south pole on the coil's lower face. If the current is now reversed in the coil, the poles of the coil will reverse, the coil will then have a north pole on its lower face, and this will be repelled by the upper north pole of the magnet. In short, the coil will rise. If the magnet is now inverted, it will, of course, attract the coil again because the upper south pole of the magnet will attract the lower north pole of the coil. If the magnet is removed altogether, the coil fails to move whether it is carrying a current or not.

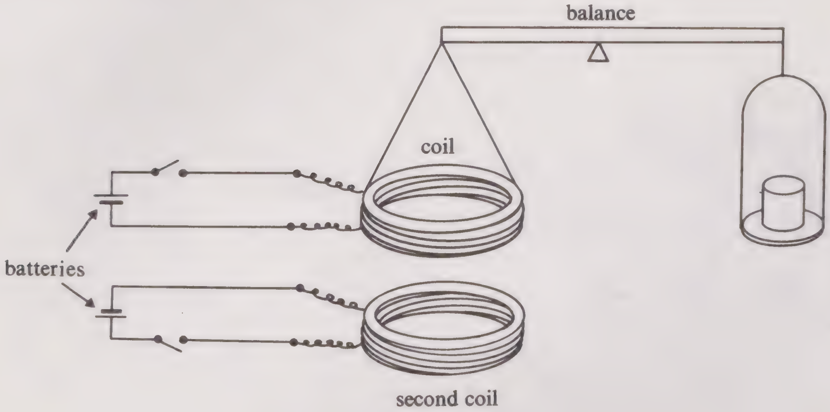


FIGURE 34 Apparatus for demonstrating the force between two current-carrying coils.

If the bar magnet is replaced by a second coil as shown in Figure 34, a similar series of experiments may be carried out—and with much the same results as long as both coils are carrying current. In other words, turning the lower coil upside down has the same effect as inverting the bar magnet in Figure 33; it reverses the direction of the force on the upper coil. Moreover, reversing the current in the second coil also reverses the direction of the force between the coils.

What general conclusion do you draw from these experiments?

It is impossible to escape the conclusion that the fields produced by current-carrying loops and coils and those produced by permanent magnets are identical. Bar magnets behave magnetically just as electric currents. But as we saw in Section 5.1, an electric current is the flow of charge-carrying electrons. So is the magnetic field produced by a bar magnet also the result of the motion of charge-carrying electrons?

Yes, it is, although the magnetic field-producing processes going on inside a bar magnet are much more complex than the flow of electrons along a wire. All materials contain electrons, each of which is in constant motion and thus produces a minute magnetic field. In other words, each electron acts as a tiny magnet. In most materials these very small electron magnets are arranged in random directions; so the individual magnetic fields cancel each other out. But in a few materials, most notably iron, complex internal forces align some of the electrons in a single direction. The nature of these forces is beyond the scope of this Course; but the result of the forces is that magnetic fields produced by the individual electron magnets no longer cancel out to zero. They now produce an observable magnetic field outside the material.

Do magnetic materials such as iron always produce magnetic fields?

No, they do not. As you saw in Home Experiment 15 (Section 2.4), when a magnetic material is heated above its Curie point, or Curie temperature, it loses its magnetism. As the temperature increases, the electrons vibrate with increasing energy; and it is this vibration which, at a critical temperature characteristic of the material (the Curie point) causes the alignment of the electrons to break down and the magnetism to be lost. If the material is allowed to cool again to below its Curie point, the electron magnets will once again become aligned; and if this happens in an externally produced magnetic field, such as that of the Earth, the alignment will be in the direction of that field*.

* This is demonstrated in TV 05.

As you will see in Section 5.7, the conclusion that bar magnets and electric currents behave similarly as far as their magnetic fields are concerned is a very important one when it comes to trying to explain the origin of the Earth's magnetic field. To reinforce the conclusion, Figures 35 and 36 show rather longer coils than we have considered so far. Such coils are called *solenoids* when they are intended to have current flowing in them. Figure 35 shows a loosely wound solenoid. The magnetic

solenoid

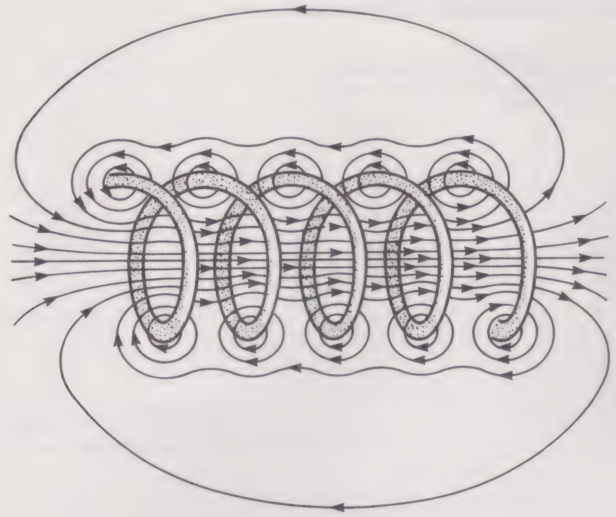


FIGURE 35 The magnetic field produced by a loosely wound solenoid.

field round a single current-carrying wire has a circular shape, but the circular fields combine to produce a field in one direction along the inside of the coil and in more or less the opposite direction outside. The same thing occurs when the solenoid is tightly wound, as in Figure 36.

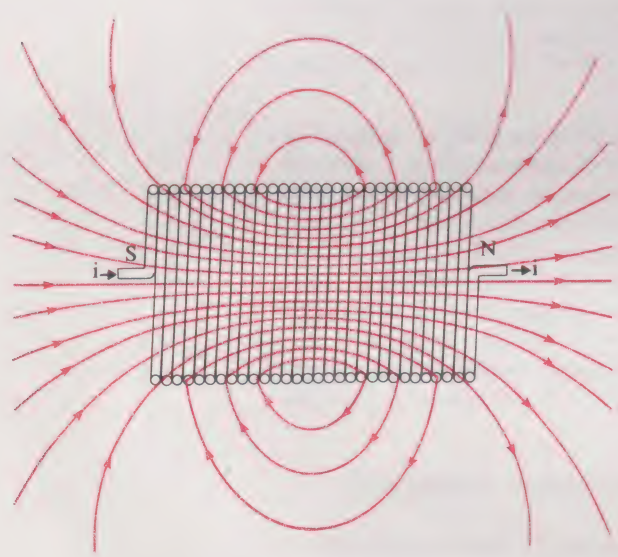


FIGURE 36 The magnetic field produced by a tightly wound solenoid.

Figure 37 shows a bar magnet with the same external dimensions as the solenoid in Figure 36. Outside, the coil and magnet fields are identical. Inside, of course, there are differences. The coil has an air core in which there is a simple magnetic field. The magnet, by contrast, has a metal 'core' in which the magnetic phenomena are very complex. The details of what goes on inside magnetic materials are far beyond the scope of this Course.

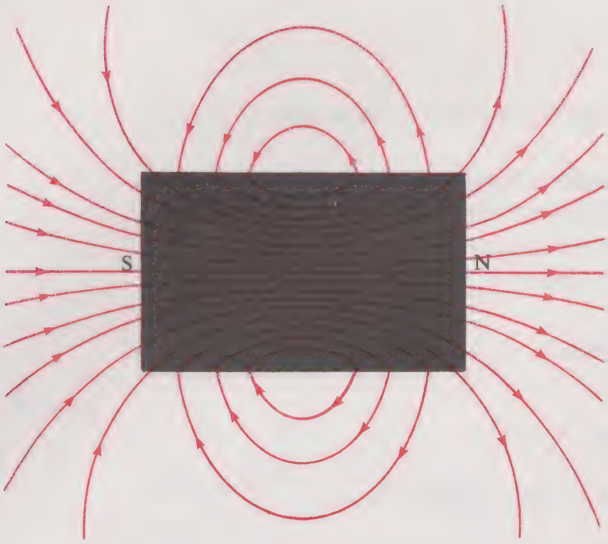


FIGURE 37 The magnetic field produced by a bar magnet having the same external dimensions as the solenoid in Figure 36.

5.2.1 Objectives of Section 5.2

(a) The only new term introduced in Section 5.2 was solenoid, a term that is easy to understand.

(b) Your ability to predict the directions and relative magnitudes of magnetic forces, restricted in Section 5.1 to straight current-carrying conductors, should now be extended to current-carrying loops and solenoids and their reactions with bar magnets.

(c) You should now also be able to illustrate diagrammatically the shapes of the magnetic fields produced by a straight current-carrying conductor, a solenoid and a circular current loop.

SAQ 14 (*Objective* (*b*))

Decide whether the force in each of the six systems (a)–(f) in Figure 38 is one of attraction or repulsion. Is the force in (b) greater or smaller than the force in (d)?

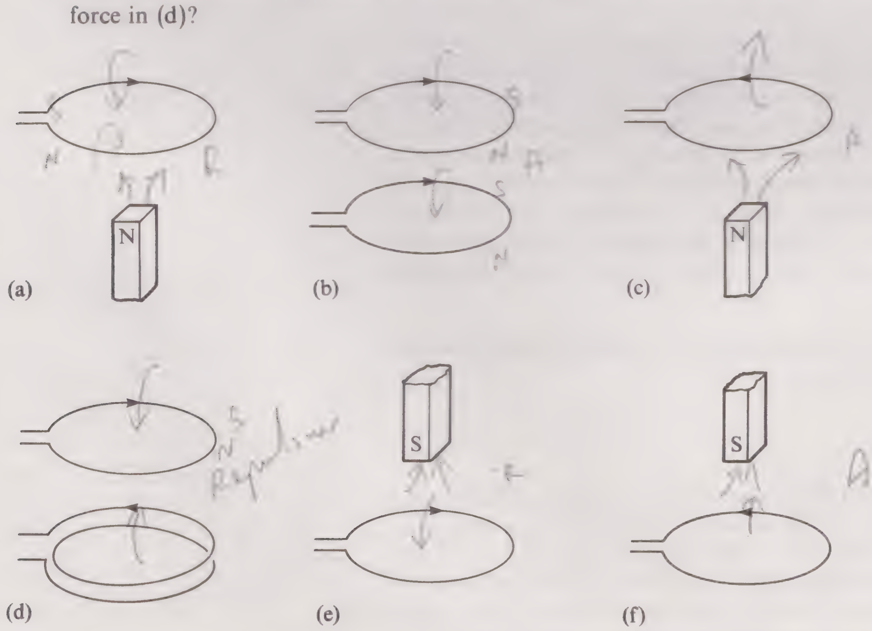


FIGURE 38 Diagram for SAQ 14. The circular loops all have the same cross-sectional area and carry the same current, and the magnets all have the same strength.

SAQ 15 (*Objective* (*c*))

Sketch the magnetic fields produced by:

(a) a vertical wire in which a current is flowing upwards (view of field from above).

(b) a single vertical loop in which the current is flowing clockwise when viewed from the right (view of field when looking at loop edge on).

(c) a tightly wound horizontal solenoid in which the current is flowing anticlockwise when viewed from the left (view of field from side of solenoid).

In each case indicate the direction of the field.

5.3 Magnetic fields of distorted current loops

A current flowing round a circular path produces a dipole magnetic field.

Figure 39a shows a current flowing in a circular path (black). What is the direction of the magnetic field through the loop (i.e. is it going down into, or coming up out of, the paper)? Which magnetic pole is the closer to you as you look at the loop?

As you look at the loop the current is flowing in a clockwise direction; so the magnetic field inside the loop is directed down into the paper (Figure 28). Moreover, since magnetic fields are directed inwards towards south poles and outward from north poles, the upper face of the loop will be the south pole.

Now suppose that the current loop is not perfectly circular but is slightly distorted (the red loop in Figure 39a). Will the magnetic field be the same as before, that of a simple dipole? Or will it be modified?

As you can see, the distorted loop is slightly elliptical in shape. If it were to be deformed even more it would look like the even more elliptical loop in Figure 39b. And if it were to be deformed to the limit it would come to form a very long ellipse (about $1\frac{1}{2}$ times as long as the diameter of the original circle, in fact) of practically zero width (Figure 39c).

Will the magnetic field produced by a current going around the red loop be the same as that produced by the same current going round the black loop? In other words, will the field from the distorted loop be dipolar?

No, it will not. The extremely distorted loop in Figure 39c is really little more than two parallel wires with the same current flowing in opposite directions. The effects of the currents will therefore cancel; there will be practically no field at all, except perhaps at the very ends. Indeed, if the two sections of the wire could be made absolutely coincident, they would produce no magnetic field anywhere. With less distortion from a circular loop, the deviation of the magnetic field from that of a dipole is, of course, less. In particular, the deviation produced by the red loop in Figure 39a is very small. In summary, then, as we progress from a perfectly circular loop to greater and greater distortion, the magnetic field begins as a dipole and deviates more and more from it until the field almost disappears altogether.

The magnetic field produced by the red loop in Figure 39a must be more complex than that produced by the black loop.

Why must it be?

Because, as we saw in Section 2.3, the dipole field is the simplest field that can exist. Any distortion of it, however small, must therefore result in a field more complex than that of a dipole. Moreover, a field more complex than that of a dipole cannot, by definition, be a dipole field; it must be a non-dipole field. At least, that is one way of looking at it. The other way is less easy to explain. Although we will not prove it to you (because the proof is very complicated), the field produced by the red loop in Figure 39a may be regarded mathematically as the sum of a dipole field and a relatively small non-dipole field. Likewise, the field produced by the red loop in Figure 39b may be regarded as the sum of a dipole

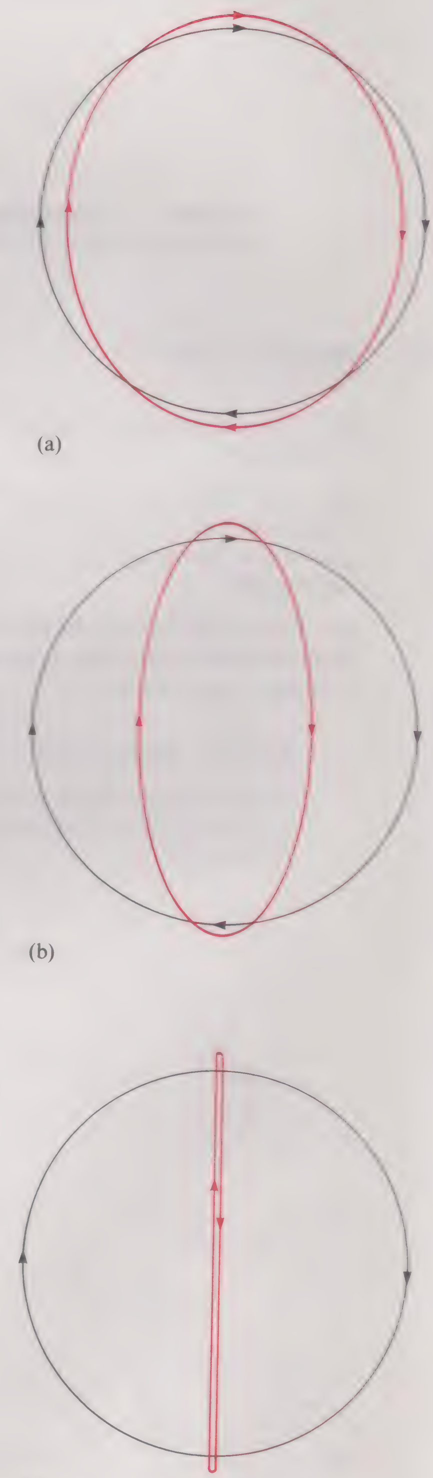


FIGURE 39 Three stages (red) in the distortion of a circular (black) current loop.

field which is weaker than that in Figure 39a and a non-dipole field which is stronger than that in Figure 39a.

The simple distortion shown in Figure 39a—squashing the original circle in at two places and stretching it out at two others to form a regular pattern—produces four small deviations from a dipole field. The non-dipole part of the field is therefore called a quadrupole field. Of course, more complicated, or higher order, distortions are possible. The distortion in Figure 40 produces a non-dipole field known as an octupole field. Moreover, although we have so far distorted our current loop in a very symmetrical way, it is possible to imagine much more irregular distortions. For example, the red loop in Figure 41 has many small irregular distortions. Because it is almost circular it would produce a field which is almost dipolar, but there would also be a variety of non-dipole components (quadrupole, octupole, etc.)

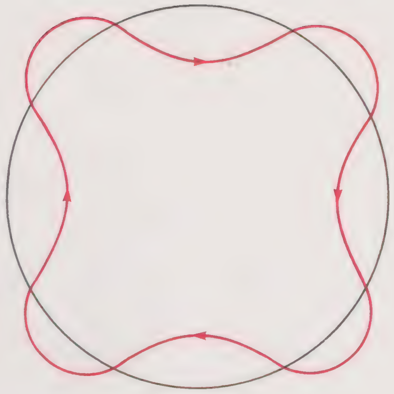


FIGURE 40 Regular distortion (red) of a circular (black) current loop: eight deviations from circularity.

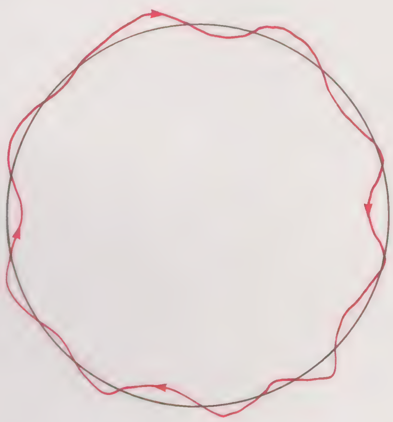


FIGURE 41 Irregular distortion (red) of a circular (black) current loop.

5.3.1 Objectives of Section 5.3

The only new words introduced in Section 5.3 were quadrupole and octupole, but you do not need to remember these.

(a) What we have done in this Section is to show you one way in which non-dipole fields may be produced and the relationship of such non-dipole fields to dipole fields. You should therefore be able to explain one possible origin of non-dipole fields.

SAQ 16 (*Objective (a)*)

Describe in not more than 100 words (and no diagrams) the way in which a non-dipole field may arise.

5.4 Modelling the Earth's magnetism: what facts must the model fit?

A plausible model of the Earth's magnetic field must be able to explain *all* the known characteristics of the field and should at the same time be consistent with the model of the Earth's interior derived from seismic wave data (Unit 4). Before we go any further, however, you should try to compile a list of the Earth's field characteristics that must be taken into account. Then check your list against ours:

1 The field has existed for at least 2 600 million years (Section 4.3).

2 The field is predominantly dipolar (Section 2.2).

3 The dipole is axial *on average* (Section 4.4).

4 The dipole is not static but fluctuates in both direction and strength (Sections 4.1, 4.4 and 4.5).

5 The field includes a significant non-dipole component (Section 3.2).

6 The non-dipole component is not static either; indeed, it fluctuates in strength and direction much faster than does the dipole field (Section 4.1).

7 The dipole field has reversed on numerous occasions throughout geological time (Section 4.6).

In addition to these field-related facts, two other points are relevant:

8 The Curie points of all known magnetic materials are below 1 200 °C and most are below 800 °C (Section 2.4).

9 The temperature rises rapidly with depth in the Earth, reaching 1 200 °C at a few hundred kilometers below the surface (Unit 4).

In the light of these factors we can look at various possible Earth models in turn.

5.5 A permanent magnet inside the Earth?

In his book *De Magnete*, published in 1600, William Gilbert suggested that the Earth is a spherical permanent magnet. At that time this seemed the only possible explanation, for a spherical magnet was known to give a dipole field (or at least a field identical to that of a bar magnet). In any case, no other source of magnetism could be envisaged.

Why is this model implausible?

Now you should see the significance of the heating experiment you carried out in Section 2.4. The combination of factors (8) and (9) in Section 5.4 means that at more than a few hundred kilometres below the Earth's surface the temperature is just too high for any material to be magnetic. Of course, it is possible that the supposed permanent magnetism of the Earth resides not in the deep interior but in a thin outer shell whose temperature is lower than the Curie point of some crucial magnetic mineral. But the rocks in the Earth's outer shell are known to be much too weakly magnetic to be able to produce a field as strong as the Earth's.

Can you think of any other argument against a permanently magnetic Earth?

Parts of the Earth's magnetic field (especially the non-dipole components) change very rapidly; and the dipole even reverses. If parts of the solid Earth had moved in such a way as to produce such spectacular changes, the Earth would have disintegrated long ago.

5.6 A consequence of rotation?

By the middle of this century several other theories had been put forward, but none had proved successful; and so scientists were forced to consider any idea, however unusual it might be. Thus, in 1947, P. M. S. Blackett, a distinguished physicist, revived and modified an hypothesis which had been suggested over 20 years before: that perhaps magnetism is a fundamental property of a massive rotating body. In other words, he was suggesting that massive rotating bodies might produce magnetic fields *just because they are rotating.*

This theory, too, soon proved to be unsuccessful. One of the predictions from the theory, as formulated by Blackett, was that the horizontal component (B) of the geomagnetic field should decrease with depth below the Earth's surface. However, Runcorn made measurements of the geomagnetic field in mines and found that the horizontal component increases with depth. Furthermore, Blackett himself used very sensitive equipment in an attempt to detect directly the magnetic field supposedly produced by rotating gold cylinders. No field could be detected.

5.7 Circulating currents in the Earth?

Among the factors (1)–(7) listed in Section 5.4, there were several accounted for by neither the permanent magnet model nor the rotating mass model.

Which were they?

They were (4), (6) and (7), all of which involve geomagnetic field variations, some of them rapid. The fact is that the Earth's magnetic field is far from stable; and any viable theory for the origin of the geomagnetic field must be able to accommodate rapidly changing fields on a global scale. However, both of the simple theories we have mentioned appeal to an origin in the solid part of the Earth. There are no known fluid permanent magnets, for example. Thus, even if these theories were successful in explaining the geomagnetic field as it is now, they would be completely at a loss to explain the changes in the field. For the only way in which rapid field changes could be produced in the solid Earth would be by vast, rapid movements of solid material or extremely large and rapid temperature variations. In either case the consequences would be catastrophic.

So where in the Earth are rapid changes or movements most likely to occur?

The obvious place to look for the source of the geomagnetic field is not in the solid Earth but in that part of the Earth's interior which is fluid.

Which part of the Earth is that?

The Earth's liquid outer core. We know that circulating currents can produce magnetic fields. We also believe (Unit 4) that the liquid outer core consists mainly of iron, which is a good conductor of electricity. Is it conceivable that the Earth's

magnetic field could be caused by the circulation of electric currents in the liquid outer core? It seems to be the only possibility not ruled out by the facts listed in Section 5.4.

You will remember that in Sections 5.1 and 5.2 we examined at some length the interactions of current-carrying conductors and magnetic fields—fields either from other current-carrying conductors or from magnets. One of the things we found was that a current-carrying conductor reacts with a magnetic field to produce a force which leads to motion. Now, it is an experimental fact that this phenomenon also occurs 'in reverse'. If a conductor not carrying a current is moved in a magnetic field, it will have a current produced in it*. This is known as an *induced current*; the current is induced in the conductor, but only as long as the conductor is moving. When the conductor stops, the current stops. This is the principle of the *dynamo*. The principle of a very simple mechanical dynamo is illustrated in Figure 42. A solenoid is located beneath a copper disc which is mounted on an axle; and a wire goes from one side of the disc to the axle via the solenoid and a meter which can indicate a current. There are rubbing contacts (brushes) on the disc and the axle.

induced current

dynamo

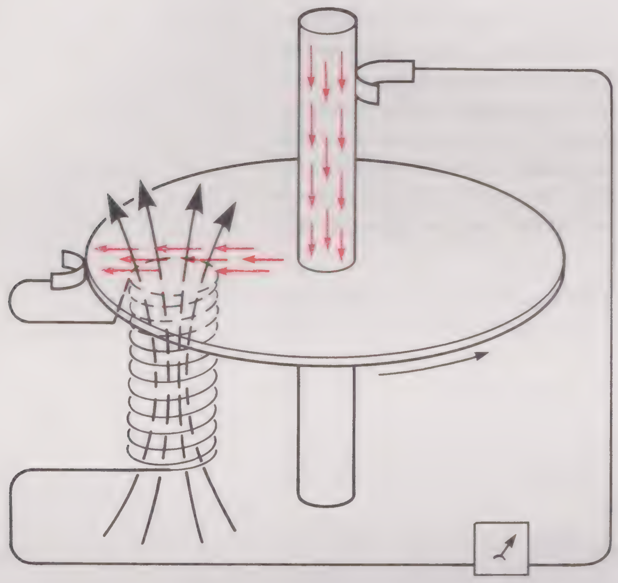


FIGURE 42 A simple mechanical self-exciting dynamo.

Suppose that a battery is used to produce a current, and hence a magnetic field, in the solenoid. If the copper disc is now rotated by hand, and kept spinning, a current is generated in the direction shown by the straight arrows, because the conducting disc is moving in the field from the solenoid. This is the dynamo action. But a current flowing in a conductor produces a magnetic field; and so the current induced in the copper disc and axle will itself produce a magnetic field. This new magnetic field will, in turn, induce a further current in the disc and axle; and this current will then produce a magnetic field. And so on. The magnetic field produced in the solenoid by the battery is now no longer required; the battery may be disconnected without affecting the working of the dynamo.

So we have here not just a simple dynamo, but a dynamo which produces its own magnetic field. This is known as a *self-exciting dynamo*. As long as there is a non-uniform magnetic field there right at the start to set the process off, and as long as there is a source of energy to keep the disc turning, the self-exciting dynamo should maintain a magnetic field for ever.

self-exciting dynamo

Of course, there is no copper disc near the centre of the Earth. But there is a conductor—the iron of the fluid outer case. And it is at least conceivable that the core contains a source of energy. For example, if there are heat sources in the core, the temperature there will rise. Heat will be lost by conduction to the mantle; and so even if the heat sources are distributed evenly, the outer parts of the core will be

* The current is only produced if the conductor forms part of a complete circuit, and is not produced if the field is uniform (that is, if the field is everywhere constant in magnitude and direction), unless the angle between the conductor and field direction changes.

cooler than the deeper parts. Because a decrease in temperature produces an increase in density, there will be denser material towards the outside of the core. The cooler, denser material will then sink and the hotter, less dense material deep in the core will rise. In other words, the core material will move around by *thermal convection.*

thermal convection

The most probable source of heat is radioactivity. We shall deal with the phenomenon of radioactivity in greater detail in Unit 10. In brief, however, a radioactive substance is one that spontaneously emits certain particles and rays, and changes into a completely new substance in the process. During this change, or decay, heat is also released. The three radioactive elements that are important in the Earth, because of their high heat production, are uranium, thorium and potassium.

Finally, the initial magnetic field required to start the Earth dynamo does not pose much of a problem. It could, for example, have been a stray field—possibly from the Sun.

But is there really a self-exciting dynamo in the Earth? No one really knows whether motions exist in the Earth's core, let alone what form they might take. If there are motions in the core, however, they are likely to be extremely complex. The problem is intractable in the real situation. Nevertheless, it has been possible to show mathematically in a general way that there do exist motions within a spherical fluid conductor which could cause it to act as a self-exciting dynamo. This does not mean that these particular motions are the ones, or are anything like the ones, that actually occur in the Earth. But at least it has been possible to show that the self-exciting core dynamo is feasible. Moreover, it is possible to conceive of, and even build, electrical and mechanical devices that illustrate the physical principles of the self-exciting dynamo.

There are two further points worth noting about motions in the core. First, their complexity is unlikely to lead to perfectly circular flow and hence the production of a pure dipole field. Distorted motions are only to be expected, leading to the production of non-dipole fields by the mechanism described in Section 5.3. Moreover, however simple the flow may be in the body of the fluid outer core, motions will be heavily modified where they come into contact with the relatively stationary mantle. Eddies will be formed at the outer edge of the core and may well lead to the production of small dipole fields.

The second point is that motions in the core are likely to be influenced by the motion of the Earth as a whole, namely, the Earth's rotation. It is not unreasonable, therefore, to suppose that the axis of the Earth's dipole will coincide *on average* with the rotational axis. After all, the dipole must point in some direction; and the rotational axis is the only axis in the Earth which can be distinguished from all others. But why should the dipole point one way rather than the other along the rotational axis? The two opposed directions (north to south, south to north) are indistinguishable; and on average one would expect the dipole to lie in each direction for about 50 per cent of the time.

Does this happen?

Yes it does, as field reversals demonstrate (Section 4.6). If you examine Figure 23 carefully you can see that, for the past 4–5 million years at least, the geomagnetic field has been normal for about half the time and reversed for the other half.

On the subject of reversals, an interesting point about the self-exciting dynamo shown in Figure 42 is that with the disc rotating in a given direction, you can produce a current that goes through the axle, disc and solenoid, *in either direction*, and hence a magnetic field from the solenoid *in either direction* (N pole up or N pole down) depending *only* on the direction of the initiating current and magnetic field. If the circulating current is interrupted for some reason, there will be no magnetic field from the solenoid. If a stray magnetic field, for instance from another dynamo that is just starting up nearby, sets the current going again, the direction of that current, and of the field produced by the solenoid, will depend only on the direction of that stray magnetic field. It could be the reverse of the direction it had before.

This suggests a possible process by which the Earth's magnetic field could reverse from time to time.

It seems likely that there is not just one great big circulating current in the outer core, one great big self-exciting dynamo, but a large number of eddies and whorls produced by the combination of the Earth's mainly rotational motion and thermal convection currents—a large number of closely coupled dynamos whose magnetic fields add up to a mainly axial dipole field plus the irregular non-dipole components. The behaviour of one of these dynamos could be strongly affected by the behaviour of its neighbours. If the current flow in one dynamo stopped, or got twisted up so as to produce a momentary cancelling out of its magnetic field, then the direction in which it started up again would depend upon the direction of the stray magnetic field produced by the neighbouring dynamos. It is conceivable that reversals could spread in this way until the magnetic field produced by the combination of all the circulating currents is itself reversed.

Of course this is sheer speculation, but it is the best we can do. The problem of exactly what combinations of motions and currents in the Earth's outer core could produce precisely the effects observed is obviously a very difficult one, which is likely to keep theoretical geophysicists puzzling for quite a time!

5.8 Objectives of Sections 5.4–5.7

(a) The only new terms in Sections 5.4–5.7 that you should now understand and be able to answer questions on are induced current, dynamo, self-exciting dynamo and thermal convection.

(b) We have looked at three different models of the Earth's magnetism, all of which you should now be able to describe. You should also be able to explain why the two simple models cannot be valid and how the complex model accounts for the known features and variations of the geomagnetic field.

SAQ 17 (*Objective (b)*)

The earliest theory for the origin of the geomagnetic field appealed to permanent magnetism in the Earth. Which of the statements below are relevant to the case against this theory?

(a) Rotating gold cylinders produce no detectable magnetic field.

(b) Every magnetic material possesses a Curie point.

(c) Rapid large-scale movements of solid material do not occur in the Earth.

(d) The temperature in the Earth increases with depth below the surface at the rate of about 30 °C per kilometre.

(e) Runcorn found that the horizontal component of the geomagnetic field increases with depth below the Earth's surface.

(f) The Earth's crust and upper mantle are very weakly magnetic.

(g) Secular variations of the geomagnetic field are very rapid.

(h) The shape of the magnetic field produced by a roughly spherical magnetic body is similar to that produced by a magnetic dipole.

SAQ 18 (*Objective (b)*)

What are the three chief pieces of evidence against the idea that magnetism is a fundamental property of rotating bodies?

SAQ 19 (*Objectives (a) and (b)*)

Which of the expressions below are consistent with a self-exciting dynamo model of the origin of the geomagnetic field?

(a) The Earth's fluid core is a good conductor of electricity.

(b) A conductor forming part of a complete circuit, which moves in a magnetic field, has a current induced in it.

(c) The Earth possesses a solid inner core.

(d) Thermal convection currents exist in the fluid core.

(e) Earthquake energy is released in the upper mantle.

(f) The Earth's field reverses.

(g) An initial magnetic field is required.

6 Planetary magnetic fields

The whole of the self-exciting dynamo model for the origin of the Earth's magnetic field rests on the liquid nature of the metallic outer core. So compelling is the evidence that the magnetic field must originate in a liquid metallic core, that the existence of the magnetic field becomes further evidence that the outer core must be liquid! In the case of the Earth, of course, we have independent evidence, from seismic waves, that this must be the case. But what about the other planets?

Of the four terrestrial planets, the Earth has far and away the strongest magnetic field. Venus, the planet which is most like the Earth in size, mass and density, does not have a magnetic field at all. Because Venus is so similar to the Earth, it is logical to suppose that it has a core of broadly similar nature. But the absence of a magnetic field suggests that, even if its core is liquid, it is not moving about very much. This may in turn be the result of the very slow rotation period.

Mercury has a very large, dense iron core. But because the planet spins so slowly on its axis (once every 59 days), it may seem initially as though Mercury, like Venus, should lack a magnetic field. The observations, however, show just the opposite—Mercury *does* have a field, albeit weaker than the Earth's. This discovery has surprised scientists, and some are now suggesting that Mercury has a *permanent* field, like that originally invoked for the Earth.

Mars is a low-density planet, which therefore probably lacks a metallic core; therefore it is not surprising to find that it does not possess a significant magnetic field. The Moon has roughly the same density as Mars; it does have a core, which may be partly liquid, but it has only an extremely weak magnetic field. Returned samples from the Moon, however, were subjected to palaeomagnetic examination, and these showed that the Moon originally possessed a very much stronger field than it has now. One possibility is that at one time movements in the Moon's core may have been much more active than they are now. It is also possible that the Moon, like Mercury, may retain some permanent magnetism, dating from a time when it may have been exposed to very powerful fields from the Sun.

The only other planet known to have a magnetic field is Jupiter. Indeed, Jupiter's magnetic field was the first planetary field to be discovered after that of the Earth. Strangely, Jupiter's dipole axis is also inclined to the rotational axis by 11°, although this is probably a coincidence.

7 Summary of Unit 5

We began this Unit by considering the basic properties of bar magnets. This led naturally to a consideration of the shapes and magnitudes of magnetic fields, especially the field produced by a magnetic dipole. The characteristics of the geomagnetic field were then reviewed, and the field throughout the periods covered by direct observation and the rock record was interpreted as predominantly dipolar but with a non-dipole component. All features of the Earth's field were seen to change with time, some rapidly—a fact which suggested that the Earth's liquid outer core is the only possible field source.

Before considering models for the origin of the Earth's field, we saw how magnetic fields could be produced by electric current-carrying conductors, especially loops and coils. Indeed, we found that loops and coils not only produce magnetic fields, they produce dipole fields similar to these produced by bar magnets and the Earth. This gave us a clue to the generation of the Earth's field, for, upon examination, theories involving permanent magnetism or rotation effects proved untenable. By contrast, a model based on circulating currents was capable not only of explaining the origin of the Earth's dipole but also of accounting in general terms for the non-dipole components superimposed upon the dipole.

Finally, we looked very briefly at the magnetic fields of the planets, where such fields exist.

As far as the Earth's magnetic field itself is concerned, we have given most attention to observations. This is because it is far easier to observe the field directly,

and even, via palaeomagnetism, to extend these observations back in time for hundreds of millions of years, than it is to formulate a detailed theory for the origin of the field. If, as seems likely, the geomagnetic field is produced by some process in the Earth's core, the precise details of this process are likely to be complex.

Aims and Objectives

Apart from Objective 1, which relates to all the terms and concepts used in this Unit, the Objectives may be divided into three groups which are related to the Aims of this Unit as follows:

Aims

1 (*Objectives 2, 3, 4 and 5*) To describe some of the basic properties of magnetic fields produced by magnets and electric currents.

2 (*Objectives 6, 7, 8 and 9*) To describe the main features of the Earth's magnetic field and their variations with time.

3 (*Objectives 10, 11 and 12*) To propose a model of the origin of the Earth's magnetism which is consistent with the known data about the geomagnetic field and with the known structure of the Earth's interior.

Objectives

1 Define correctly, recognize the best definitions of, and distinguish between true and false statements concerning the terms, concepts and principles listed in Table A.

2 Describe the simple conspicuous properties of a bar magnet (dipole) and its magnetic field (SAQs 1, 2, 3 and 4).

3 Illustrate diagrammatically the shapes of the magnetic fields produced by a straight current-carrying conductor, a circular current loop and a solenoid (SAQ 15).

4 Explain what is mean by a 'non-dipole field' with reference to circular current loops which have been distorted (SAQ 16).

5 Predict the directions of the magnetic forces between straight current-carrying conductors, bar magnets, current loops and solenoids (SAQs 13 and 14).

6 Describe the main features of the Earth's present magnetic field (SAQs 6, 7 and 8).

7 Illustrate diagrammatically the definitions of the magnetic elements and recognize the truth or falsity of statements relating to those definitions (SAQ 5).

8 Describe, in words and diagrammatically, how the Earth's dipole and non-dipole fields have changed over the period covered by direct observations (SAQs 9, 10 and 11).

9 Describe, in words and diagrammatically, the main changes in the geomagnetic field as deduced from the magnetism of rocks and artefacts (SAQs 10, 11 and 12).

10 Describe two simple models of the Earth's magnetism (those of Gilbert and Blackett) which are untenable and explain why they are untenable (SAQ 17).

11 Describe qualitatively the main features of the circulating current model of the Earth's magnetism (SAQ 18).

12 Explain how the circulating current model of the Earth's magnetism accounts for the known facts about the Earth's magnetic field (SAQ 19).

ITQ answers and comments

ITQ 1

Home Experiment 1

The sharp end of the compass needle points approximately north. The compass needle is, of course, a magnet. The sharp end is the *north-seeking pole*, a term usually abbreviated to *north pole*. The blunt end of the needle is the *south-seeking pole*, or *south pole*.

Home Experiment 2

When suspended in this way a magnet acts as a compass needle. If free to rotate it will come to rest approximately north–south. The end of the magnet pointing north is the north-seeking or north pole by definition; likewise the opposite end is the south-seeking or south pole.

Home Experiment 3

There is an attractive force between the north pole of one magnet and the south pole of the other. And there is a repulsive force between, on the one hand, the two north poles and between, on the other hand, the two south poles. Thus like poles repel each other and unlike poles attract each other—phenomena that may be confirmed using the compass needle.

Home Experiment 4

As the magnets come together you can feel the force between them increasing, whether it is *attractive* or *repulsive*. When the magnets get very close together the force increases very rapidly indeed.

Home Experiment 5

In the arrangement in Figure 8 the north pole of the magnet has attracted the south pole of the compass needle so that the needle lies along the axis of the magnet. If the second magnet is brought up slowly towards the needle as shown in Figure 43, the north pole of this magnet will also attract the south pole of the needle. When the magnets, assumed to be equal in strength, are at the same distance from the needle, the forces they exert on the needle are equal but in opposite directions. The *resultant* force on the needle is therefore zero—that is, the needle experiences no net force at all and thus lies in the same direction as it would if the magnets were removed completely. What this experiment shows is that magnetic forces and fields from separate sources may be added together (always taking their directions into account, of course).

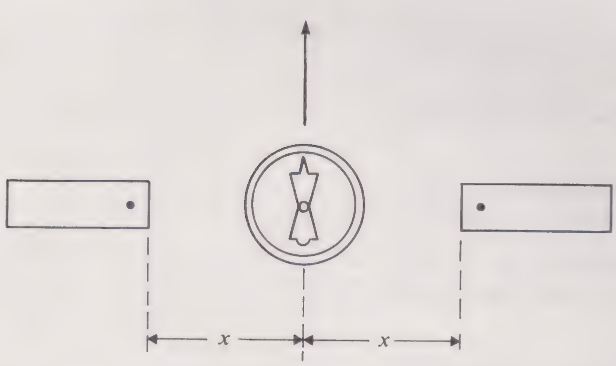


FIGURE 43 The cancellation of magnetic fields by bar magnets of equal strength.

Home Experiment 6

Some materials are attracted by a magnet and some are not. The objects you could lift with a magnet almost certainly contained iron or steel. There are a few other strongly magnetic materials, such as nickel and cobalt, but they are much less common than iron.

Home Experiment 7

You should be able to. Magnetic forces can penetrate certain substances.

Home Experiment 8

It should. By stroking the nail/screwdriver with the magnet you should have made the nail/screwdriver into a magnet itself. The nail/screwdriver, like the magnet, now possesses *permanent magnetism*; that is, the magnetism remains even when the magnetizing source is removed. Note that 'permanent' magnetism is not permanent in the sense that it can never be removed, as you will see in Section 2.4.

Home Experiment 9

The second and lower nails should fall off. All the nails acted as magnets as long as the bar magnet was attached; they possessed *induced magnetism*, magnetism induced in them by the bar magnet. But once the bar magnet was removed the magnetism in the nails disappeared: it was not permanent magnetism.

Home Experiment 10

The second and lower pins should not fall off. As with the nails, when the pins were attached to the bar magnet they possessed induced magnetism. When the bar magnet was removed the induced magnetism disappeared, but the pins were nevertheless left with some permanent magnetism. Materials which can acquire permanent magnetism as easily as this are called magnetically 'soft'. By contrast, the nails in Experiment 9 were magnetically 'hard'. With magnetism, however, it is a case of easy come—easy go. A magnetically soft material readily acquires permanent magnetism but equally easily loses it. By contrast, the permanent magnetism acquired with greater difficulty by the magnetically hard material is difficult to remove.

Home Experiment 11

Yes, they do. The pattern you have obtained should look like Figure 44.

Home Experiment 12

You should observe that the iron filings form a pattern which resembles that made by the directions in Home Experiment 11. The iron filings link up in lines which lie in the same directions as the arrows in Figure 44. You should also observe that there is a tendency for the iron filings to concentrate around the two magnetic poles. This is because the magnetic fields around the poles are stronger than elsewhere.

Home Experiment 13

When the magnet is present, the iron filings contain induced (non-permanent) magnetism just like the suspended nails in Experiment 9. When the magnet is removed, the induced magnetism disappears and with it the pattern in the iron filings.

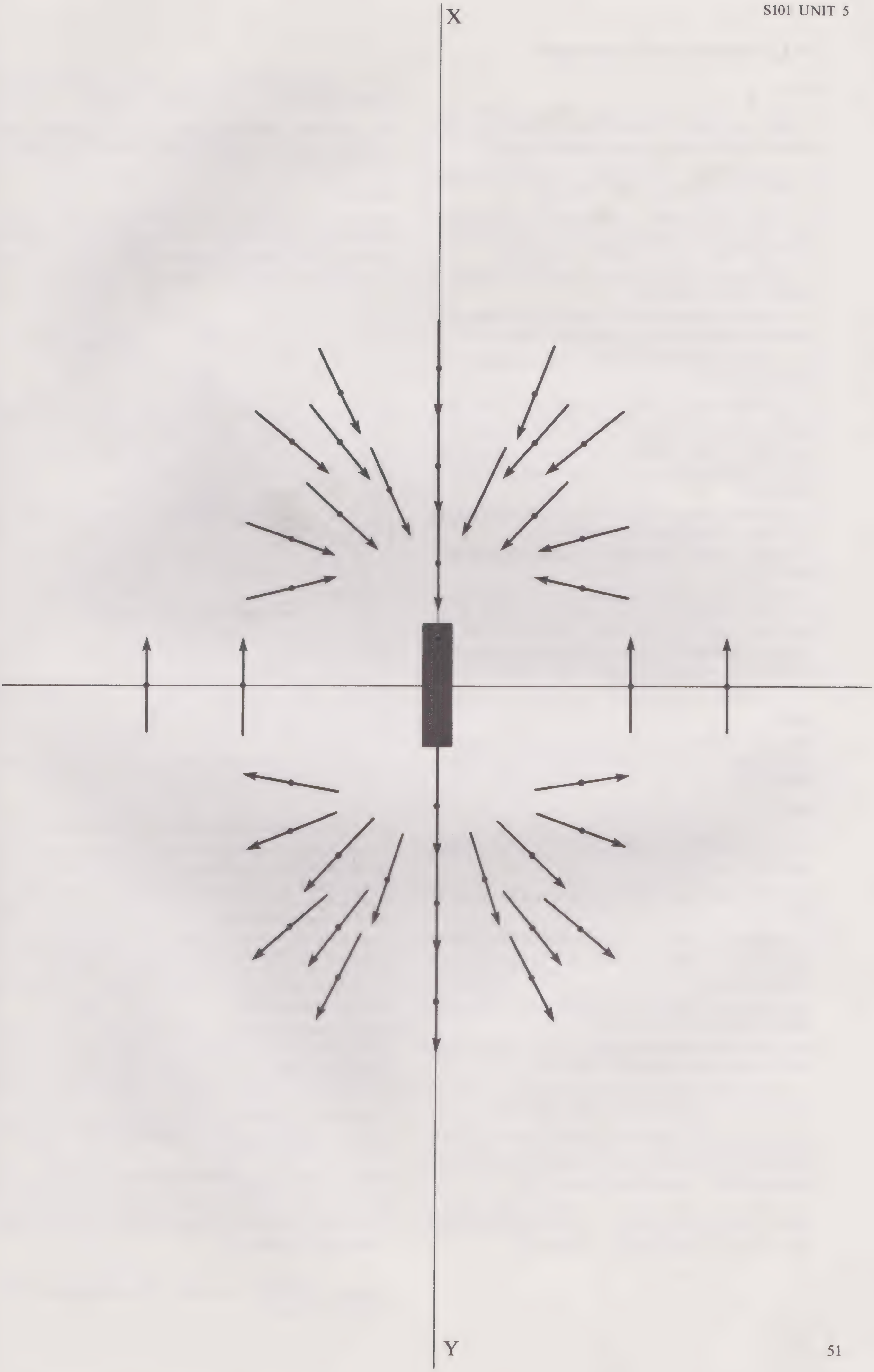
Home Experiment 14

The results are given in the Main Text.

Home Experiment 15

The results are given in the Main Text.

Opposite FIGURE 44 The magnetic field from a bar magnet with the north pole pointing south.


X
Y

SAQ answers and comments

SAQ 1

(a) (i) Iron. The other, but less common, natural magnetic metals are nickel and cobalt. In addition, man-made alloys (e.g. steel) containing iron are usually strongly magnetic. (Section 2.2)

(b) (i) South (ii) North. As Experiment 3 showed, like poles repel but unlike poles attract each other. (Section 2.1)

(c) (i) Zero. As Experiment 5 showed, magnetic fields may be added together, taking into account the field directions. Equal but opposite fields thus cancel out. (Sections 2.1 and 2.2)

(d) (i) Magnetic meridian. This is, of course, the definition of magnetic meridian. (Section 2.1)

(e) (i) South. A compass needle is a magnet, so the normal laws of attraction and repulsion apply as in (b) above. (Section 2.1)

(f) (i) Permanent. This is the definition of permanent magnetism. (Section 2.1)

(g) (i) North-seeking (ii) North. North-seeking and north mean the same in this context. It is merely a convention that compass needles are magnetized in such a way as to make their pointed ends point north. In ancient China the convention was reversed; the handles of lodestone spoons usually pointed south as in Figure 1. (Section 2.1)

(h) (i) North (ii) Southern. It's a bit misleading, but that is the way things developed historically. (Section 2.2)

(i) (i) Magnetometer. Simply the name of the instrument used. (Section 2.2)

(j) (i) Hard. The 'harder' a magnetic material is, the stronger is the magnetic field required to magnetize it permanently. By the same token, however, the stronger is the field required subsequently to demagnetize it. It follows that permanent magnetism in magnetically hard materials is more stable than that in magnetically soft materials. (Section 2.1)

SAQ 2

Your sketch should look like Figure 10c; you should expect the magnetic pattern from a bar magnet uninfluenced by other fields. (Section 2.2)

SAQ 3

(a) Increases. Magnetic fields decrease with distance from their sources (the poles) and hence increase in the opposite direction. (Sections 2.1 and 2.3)

(b) Weaker. This was well illustrated by Home Experiment 12. (Section 2.1)

(c) Permanent. It cannot possess induced magnetism when well removed from the magnetizing source because, by definition, the conditions for the development of induced magnetism do not exist. On the other hand, it may or may not be left with permanent magnetism, depending on its properties, the size of the original magnetizing field, etc. (Section 2.1)

(d) Dipole. This can be ascertained by comparing Figures 2 and 10c. In any case, single poles cannot exist. (Section 2.2)

(e) Equal. If they were not equal there would be a net field in one direction; the two fields would not cancel. (Section 2.2)

(f) Move laterally. It cannot move laterally because the force on the north pole in one direction will equal the force on the south pole in the opposite direction. However, it will rotate into the field direction (unless it is already there). (Section 2.3)

(g) Against. The field direction is defined as that direction in which an isolated *north* pole would move or that direction in which the north pole of a dipole will point. (Section 2.3)

(h) $4x$. Fields in the same direction reinforce each other, so the resultant field here is $(x + 3x)$. (Sections 2.1 and 2.2)

(i) Curie point. Sometimes called the Curie temperature. Of course, magnetism is also effectively zero at a null point, but for a quite different reason. (Section 2.4)

SAQ 4

Your sketch should look like Figure 45. What is required is the combination of the field due to a bar magnet with its north pole pointing north (i.e. Figure 10c rotated through 180°) and the field of the Earth (i.e. Figure 10b as it is).

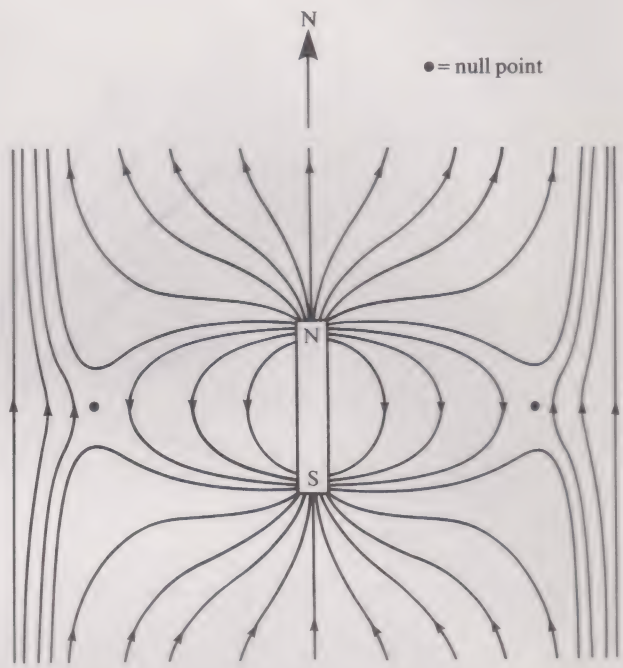


FIGURE 45 The combined field pattern from a bar magnet and the Earth with the north pole of the magnet pointing north.

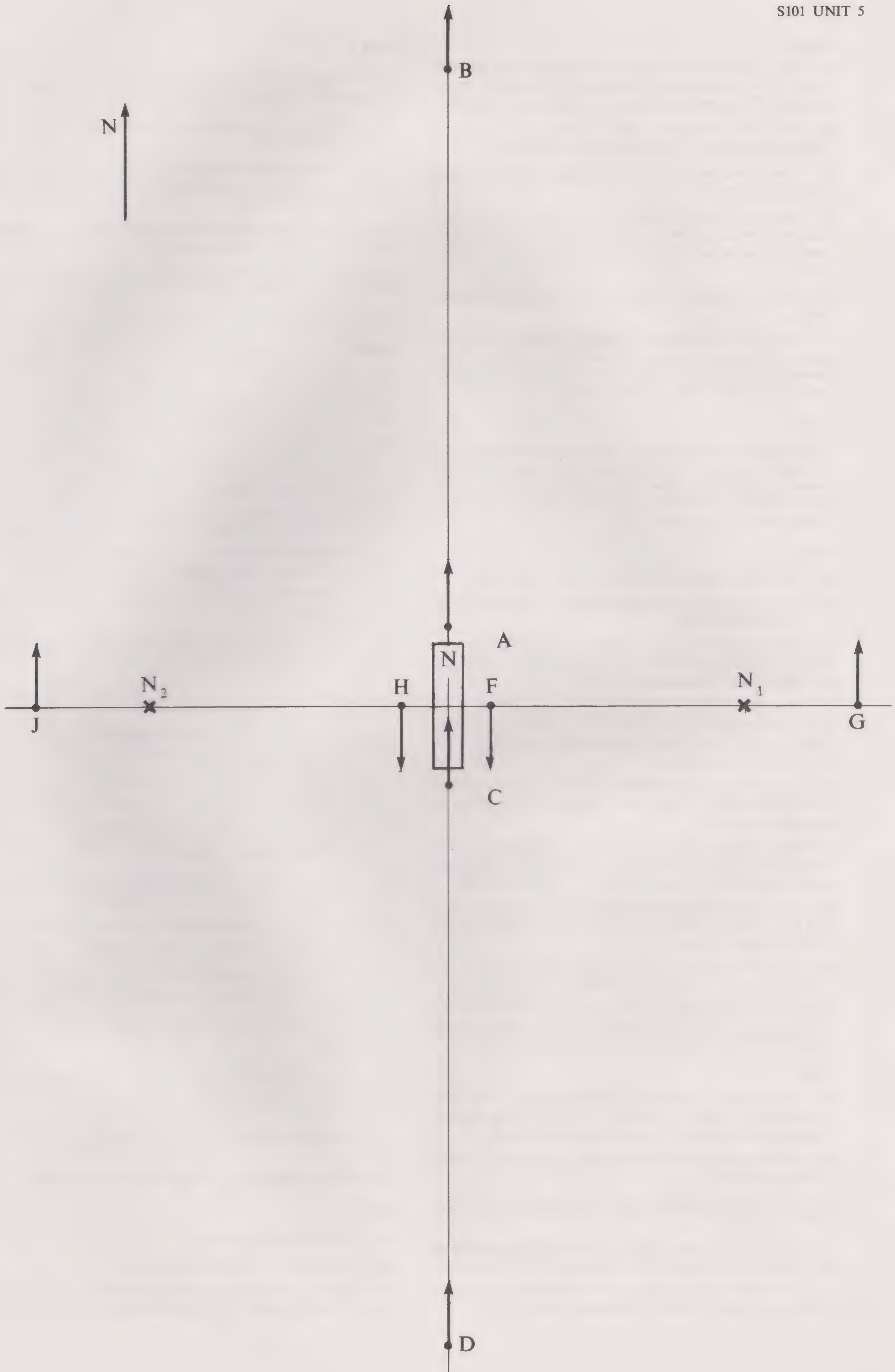
You should have been able to build up Figure 45 as follows:

The basic set-up is that shown in Figure 46. At point A the field is almost entirely due to the magnet. The field is directed outward from the north pole of a magnet—and hence in this case northward. At point B, far from the magnet, the field is almost entirely due to the Earth and the Earth's field is, of course, generally northward. There is no reason to suppose that along AB the combined field points other than north. The same argument applies to CD. At D the Earth's field predominates and points north, whereas at C the magnet's field dominates and is directed into the south pole—i.e. again northwards.

Now look at the east–west axis. At F, close to the magnet, the field of the magnet is south (cf. Figure 10c as turned through 180°). At G, well away from the magnet, the field of the Earth is north, as it always is. In other words, the field direction at F is opposite to that at G. Between F and G the field direction must change from south to north and will somewhere be zero. One null point, N_1, thus lies somewhere between F and G. By similar reasoning, the other null point, N_2, lies between H and J.

Once you have the axial field directions plotted, it should be comparatively easy to fill in the rest of the diagram, always bearing in mind that close to the magnet the magnetic field of the magnet predominates, whereas away from the magnet the Earth's field predominates. (Section 2.2)

Opposite FIGURE 46 Deduction of the axial directions for the situation in Figure 45.



B
N
A
N
N_2
H
F
N_1
J
G
C
D

SAQ 5

(a) True. The direction of the magnetic meridian is the direction in which a horizontal compass needle points. The angle between this direction and geographic north is the definition of declination.

(b) False. The statement is correct except that inclination is measured with respect to the horizontal, not the vertical.

(c) True. North-east is 45° E of N—the angle between the needle and geographic north.

(d) False. The numerical value is indeed 70° since inclination is measured from the horizontal, not the vertical. But upward inclinations are counted as negative. The inclination here is therefore −70°.

(e) False. The inclination will be 90° at the north geomagnetic pole.

(f) True. Lines of geographic longitude join the north and south geographic poles; magnetic meridians join the north and south geomagnetic poles. And for a geocentric axial dipole the geomagnetic and geographic poles coincide. (Section 3.1)

SAQ 6

The correct answer is: strongest (b); intermediate (a); weakest (c). The dipole field is by far the strongest component of the total geomagnetic field. On average the non-dipole field amounts to only about 5 per cent of the total, and the external field contributes a further few per cent. (Section 3.2)

SAQ 7

(a) True. This is simply the definition of the term 'axial'.

(b) False. At present the geomagnetic dipole is inclined at about 11° to the rotational axis.

(c) False. Most of the magnetic field observed at the Earth's surface is produced by processes occurring *inside* the Earth. Only a few per cent of the field is produced externally.

(d) True. The dipole axis cuts the Earth's surface at 79° N, 70° W (the north geomagnetic pole) and at 79° S, 110° E (the south geomagnetic pole). These points are antipodal, that is, they lie at opposite ends of an Earth diameter.

(e) False. The geomagnetic dipole is inverted, that is, its south pole points towards northern regions of the Earth where the north geomagnetic pole lies.

(f) False. At the north geomagnetic pole the inclination of the *dipole* field is +90°. But at this point the irregular non-dipole field is not zero, and so the resultant inclination differs from +90°.

(g) True. The strength of the dipole field varies from about 0.31×10^{-4} T at the geomagnetic equator to about 0.62×10^{-4} T at the geomagnetic poles.

(h) False. The magnetic dip poles are the points on the Earth's surface at which the inclination produced by the dipole and non-dipole fields acting together is either +90° (north magnetic dip pole) or −90° (south magnetic dip pole). These points are not antipodal because the non-dipole field is irregular. (Section 3.2)

SAQ 8

(a) D2. The north geomagnetic pole lies at 79° N, 70° W. This position with respect to features of the world map may be determined from Figure 15 and transferred to Figure 18.

(b) B7. The position of the south magnetic dip pole (67° S, 143° E) is shown in Figure 15.

(c) E5. Figure 16 shows that this centre lies roughly on the east coast of South America.

(d) E5 and F5. As Figure 15 shows, the 20° W line passes through the southern tip of Africa and the eastern tip of South America.

(e) E4. As Figure 17 shows, this area lies almost on the 0° longitude line just south of the African landmass. (Section 3.2)

SAQ 9

(a) (i) and (ii). Both components vary with time, although the non-dipole field changes much more rapidly.

(b) (i). This refers to the average rate of change in the longitude of the geomagnetic poles.

(c) (ii). The dipole field is regular and therefore does not produce 'centres' as the irregular non-dipole field does. It is the non-dipole field that drifts westwards.

(d) (ii). These are the characteristic periods of the non-dipole field, the 'centres' of which grow and decay.

(e) (i). Over the past 130 years or so the latitudes of the geomagnetic poles have remained more or less constant.

(f) (ii). The minimum strength of the dipole field is 0.31×10^{-4} T (at the geomagnetic equator). Any field weaker than this must therefore be a non-dipole field. However, any field strength of 0.15×10^{-4} T *actually measured at the Earth's surface* must be due to a combined dipole and non-dipole field such that the resultant field strength is lower than the minimum dipole field strength of 0.31×10^{-4} T. For example, if the dipole field strength at a point on the Earth's surface is 0.40×10^{-4} T in a given direction and the non-dipole field strength at the same point is 0.25×10^{-4} T in the opposite direction, the net field strength at that point will be 0.15×10^{-4} T. Since dipole and non-dipole fields must act together to produce a field strength of less than 0.31×10^{-4} T at the Earth's surface, the answer to this question could be regarded as '1 and 2'.

(g) (i). This is the angle between the rotational axis and the geomagnetic dipole axis over the past 130 years or so.

(h) (ii). This is the average rate of drift of the non-dipole field over the past 130 years or so.

(i) (i). This is the rate of decrease of the dipole field strength over the past 130 years or so. (Section 4.1)

SAQ 10

(a) (ii). Direct observation of the geomagnetic field indicates only that the north geomagnetic pole has moved along 79° N latitude at an average rate of 0.042° longitude a year for the past 130 years or so. It tells us nothing about what happened to the north geomagnetic pole before about 1840. All that can be said is that *if* the pole were always to move as it has moved over the past 130 years or so, it would take about 10^4 years to make a complete revolution around the geographic pole. (Section 4.1)

(b) (ii). This statement is unwarranted because magnetic rocks of that age have not yet been discovered. (Section 4.3)

(c) (ii). The average rate of westward drift of the non-dipole field over the past 130 years or so has been 0.2° longitude a year. This would mean that if the non-dipole field were to exist in its present form for 1 800 years it would move right round the Earth in that time. But it does not so persist. The features of the non-dipole field are continuously changing, so that the shape of the field today almost certainly bears little resemblance to that of 1 800 years ago. (Section 4.1)

(d) (ii). The data plotted in Figure 22 show that, far from remaining constant, the strength of the geomagnetic field has fluctuated widely over the past few thousand years. (Section 4.5)

(e) (i). Evidence for this statement comes from Figure 21. (Section 4.4)

(f) (i). The evidence for this is given in Figure 23. (Section 4.6)

SAQ 11

(i) (e). 10^4 years. (Section 4.4)

(ii) (b), (c), (d). 10–10^3 years. (Section 4.1)

(iii) (e), (f), (g). As Figure 23 shows, some reversals are extremely short; the normal Gilsa event, for example, was only a few tens of

thousands of years long. By contrast, the length of the reversed period between the Jaramillo and Gilsa events was approaching 10^6 years. (Section 4.6)

(iv) (e). 10^4 years, as shown in Figure 22. (Section 4.5)

SAQ 12

(a) (ii). The external field is only a very small proportion of the total field and therefore has little effect on the Earth's past field (about which palaeomagnetism gives information).

(b) (i). These are the chief magnetic minerals giving magnetic properties to rocks.

(c) (i). Palaeomagnetic measurements give some idea of how long the Earth has had a magnetic field.

(d) (ii). Palaeomagnetism deals only with the past field.

(e) (i). This is relevant for the same reason that (d) is irrelevant.

(f) (i). The field reversal versus self-reversal problem is solved by palaeomagnetism. (Section 4)

SAQ 13

The basic rule is that the force is attractive when currents are in the same direction and repulsive when currents are in the opposite direction. So the forces are attractive in (a), (d) and (e) and repulsive in (b), (c) and (f). (Section 5.1)

SAQ 14

(a) The current in the loop is clockwise when viewed from above; therefore the field points down; therefore there is a north pole on the lower face; therefore like poles are adjacent; therefore there is repulsion.

(b) The loops are as that in (a); therefore there is a north pole on the lower face of the upper loop and a south pole on the upper face of the lower loop; therefore unlike poles are adjacent; therefore there is attraction.

(c) The current in the loop is anticlockwise when viewed from above; therefore the field points up; therefore there is a south pole on the lower face; therefore unlike poles are adjacent, therefore there is attraction.

(d) The upper loop is as that in (a) and the lower loop is as that in (c); therefore a north pole on the lower face of the upper loop is adjacent to a north pole on the upper face of the lower loop; therefore there is repulsion.

(e) The loop is as that in (a); therefore the loop has a south pole on its upper face; therefore like poles are adjacent; therefore there is repulsion.

(f) This is (e) with the current reversed; therefore there is attraction.

The force in (b) is smaller than that in (d). The lower loop in (d) has more than one turn and hence produces a stronger magnetic field than a single-turn loop. (Section 5.2)

SAQ 15

(a) As Figure 28b.

(b) As Figure 30 but with arrows in the opposite direction.

(c) As Figure 36 but with arrows (and therefore north and south poles) reversed. (Section 5.2)

SAQ 16

Your answer should go something like this:

A perfectly circular current loop gives a dipole field. Any distortion of the loop will lead to a field more complex than a dipole field; but though technically a non-dipole field, this field need not be regarded as entirely non-dipolar. Mathematically, the more complex field is equivalent to a dipole field plus a relatively small non-dipole field. (Section 5.3)

SAQ 17

The relevant statements are (b), (c), (d), (f) and (g). Statements (a) and (e) are relevant to disproving the theory that magnetic fields are produced by massive rotating bodies. Statement (h) is one reason why permanent magnetism was considered in the first place. (Section 5.5)

SAQ 18

1 The rotating body theory predicts that the horizontal component of the Earth's magnetic field should decrease with depth below the Earth's surface, whereas Runcorn showed experimentally that this component increases with depth.

2 Very sensitive equipment failed to detect any magnetic field from rotating gold cylinders.

3 Rotating body magnetism would be unable to account for the rapid variations observed in the geomagnetic field. (Sections 5.6 and 5.7)

SAQ 19

The relevant expressions are (a), (b), (d), (f) and (g). Expressions (c) and (e) are not relevant because as far as we know neither the solid inner core nor the mantle play any direct part in the production of the geomagnetic field. (Section 5.7)

Acknowledgement

Grateful acknowledgement is made for permission to reproduce *Figure 1* from J. Needham (1962) *Science and Civilization in China*, Vol. 4, Cambridge University Press.


X
South
Y

Additional Notes, Unit 5 — An alternative view of the Earth's magnetic field

Section 3 of Unit 5 (The Earth's magnetic field) contains material which some of you may find unfamiliar and we would like to offer the following additional notes by way of further explanation and summary. We suggest you read them immediately after completing Section 3 of the Main Text.

All the comments and Figures referred to below relate to the dipole and non-dipole fields which are of *internal* origin, in the Earth's fluid outer core. The part of the Earth's magnetic field that is external in origin is small and not considered further in these notes.

Figure 13 — a cross-section of the Earth through the geographic poles — shows the way in which compass needles free to move in a vertical plane would line up along imaginary 'lines of force' (dashed red) if there were a *simple axially centred dipole magnet at the centre of the Earth* (such that the N magnetic pole coincided with the N geographic pole). Notice that the compass needle points straight down into the Earth at the poles, at 90° to the horizontal. This is the *angle of inclination*: it is 90° over the magnetic poles and it decreases regularly with latitude until reaching 0° over the equator.

> If the Earth had only a simple dipole field, axial and centred as shown in Figure 13, what would the pattern of lines of *equal inclination* (isoclinic lines) look like on a chart if drawn on the same projection as Figures 15–17?
>
> The isoclinic lines would be *straight*; moreover, they would be parallel to lines of *geographic latitude* and their values would vary from 90° at the poles to 0° at the equator.

1 The first complication to this simple picture is that, although the Earth does have a predominantly dipole field, the dipole axis is not aligned along the Earth's rotational axis which defines the N and S geographic poles. In fact, the dipole magnetic field axis is inclined at about 11° to the rotational axis, as shown in Figure 2. Viewed from *most* places on the Earth's surface, this means that the directions of geomagnetic north and geographic north are not the same. The angle between them is the *angle of declination.* Now you should realise that it is possible to start at either the N or S magnetic (dipole-only) pole, turn your back on the appropriate geographic pole and walk away keeping the two in line. If the field were totally an *inclined dipole* then there would be a straight line, a great circle (like a line of *longitude*) which passes through both magnetic poles and both geographic poles along which the declination is 0° (except between the two north poles and the two south poles).

> If the Earth had only an inclined dipole magnetic field, as shown in Figure 2, what would the pattern of lines of *equal declination* (isogonic lines) on a chart look like if drawn on the same projection as Figures 15–17?
>
> 2 On this projection it would consist of regular, smooth, slightly curved lines of *longitude*, not parallel to the geographic lines of longitude which meet at the geographic poles, but radiating from the *magnetic poles*.

Now look at Figure 15 which shows the observed lines of equal declination. There is an almost straight line of equal declination passing through the N magnetic pole, and the lines of equal declination do radiate from each pole. But there the similarity with our predictions ends. *The fact that there are any strongly curved lines and particularly, closed loops, on this Figure means that there must be something other than a simple dipole field source in the Earth.* Moreover, the two magnetic 'dip' poles are not antipodal as they should be according to the inclined dipole model: they are separated by approximately 120° of geographic longitude, not 180°! So the looped isogonic lines and non-antipodal magnetic 'dip' poles are two good pieces of evidence showing that the Earth *also* has a *non-dipole field* as well as a dipolar one.

Now consider the *strength* of the magnetic field, in other words, the *force of magnetic attraction* produced by the field at the Earth's surface. When we use a conventional compass, we are only measuring the *direction* of the maximum force in the horizontal plane XY of Figure 14. The compass needle comes to rest along OB because the largest force in the horizontal plane is in that direction. If we had a magnetometer, capable of measuring the actual *magnitude* of the attractive force in any direction, then it would record a force in all directions within the plane XY but with a maximum along OB. But the field strength also varies in the vertical plane and, because the source of the field is deep in the Earth, it reaches its absolute maximum in three dimensions in the plane OBFZ (Figure 14), in fact, along OF — defined by the *angle of inclination.* The strength of the field along OZ is known as the *vertical component* of the field, just as that along OB is the *horizontal component.*

A general property of dipole magnets is that the maximum field strength (as measured along lines like OF) varies with latitude and, looking again at Figure 13, the highest reading obtainable on our magnetometer over the equator (over E or W) is about half that obtainable over the poles (over N or S).

> Ignoring the non-dipole field again for a moment, what would a chart of equal total field strength (measured along lines like OF) look like for a simple dipole field?
>
> Because the maximum field strength at different points around a dipole varies, decreasing from the poles to the equator, the lines of equal field strength would be lines of latitude around the magnetic poles.

Although a comparison between these predictions and the observed field strength readings around the world (Figure 16) shows that lower readings are observed in equatorial latitudes rather than polar latitudes, once again the lines are nowhere near straight on this projection and there are many closed loops. Now comes a very important point: *if we subtract the 'best fit' predicted field due to a dipole from the observed field (that shown in Figure 16) we are left with a residue and this is the non-dipole field.* This non-dipole field is shown in Figure 17. (In fact, Figure 17 is for the vertical component of the non-dipole field, measured along OZ in Figure 14, but it shows the same features as if measured along OF.) Here, the loops noted in Figures 15 and 16 are emphasised: some add to the dipole field (e.g. over China) whereas others subtract from it (e.g. over W. Africa). But notice the units on Figure 17 : 10^{-7} tesla. The *highest* reading on Figure 17 is 180×10^{-7} T $= 0.18 \times 10^{-4}$ T, much less than the *average* reading for the total (dipole and non-dipole) field in Figure 16. Despite all the complications it causes, the non-dipole field is only about 5% of the total field, the other 95% is dipolar. But because of the non-dipole field, the two *dip poles* (defined as places where the inclination *is* 90°) shown in Figure 14 are not antipodal as they would be for a centred dipole-only field.

By comparing two charts for the non-dipole field, prepared from readings taken at different times (Figures 20a and 20b),

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we see that there is a general *westwards drift* of the closed loops. But they also *change in intensity*, growing and diminishing with time. Low A grew from −80 to -160×10^{-7} T, for example, in the 130 years between 1835 and 1965. This means that the effect of these highs and lows on declination, inclination and field strength charts for the whole field (such as Figures 15 and 16) will change with time both in position and intensity. So, for example, we may predict that the loop over E. Russia (Figures 15 and 16) will move to the west in the future. If it continues to increase in intensity, as it has for the past 130 years, then the *magnitude* of the 0.60×10^{-4} T loop on Figure 16 will also increase, as will the *magnitude* of the disturbance to the lines of equal declination in Figure 15. Changes in the *position* of centres such as this with time, relative to geographic latitude and longitude, can be used to calculate the *rate* of westwards drift. The *magnitude* of each centre reflects the magnitude of the non-dipole field at that point, not the position of its centres, and so changes of magnitude cannot be used to calculate the rate of westwards drift.

The sum total of all these changes on periods ranging from 10–10^3 years for the non-dipole field to 10^4 years for the dipole field are known as *secular*, or time, *variations*. They indicate that the Earth cannot have an internal permanent solid magnet and, to account for such rapid secular changes, the field must have a dynamic origin in a fluid layer (the outer core) as explained in Section 5 of the Main Text.

Finally, a word about the completely separate subject of *palaeomagnetism*, which is described in Section 4.4 and used in Units 6 and 7 to establish 'polar wander curves'. This technique uses the inclination and direction of the magnetic field recorded in ancient rocks (c.f. Figure 13 and TV5 BN) to deduce their associated *palaeopoles*. The assumption is made that the field was, in the past, axial and dipolar — the fact that this yields consistent results within 10° latitude error (Figure 21) indicates that the Earth's field, like that at present, must have been predominantly dipolar during the period represented by palaeomagnetic studies (now c. 3000 Ma).

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